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ENGINEERING AND DEVELOPMENT SUPPORT OF GENERAL DECON TECHNOLOGY FOR THE U.S. ARMY'S INSTALLATION RESTORATION PROGRAM

Task 1. Literature Review on Ground Water Containment
and Diversion Barriers

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Prepared for:

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Aberdeen Proving Ground, Maryland   21010

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protection	sheet piling	

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report presents a review and evaluation of the available information on the use of physical and hydrological barriers for containment or diversion of ground water. The types of barriers investigated included slurry-trenches, grout curtains, Imper-walls, sheet piling, French drains, wellpoints and pump-back wells. The state-of-the-art technology for each of these barriers is discussed. Advantages and disadvantages of each method, application to particular ground water control scenarios, and costs for a standard 1067 m barrier are presented.

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SUMMARY

The available literature on methods for containment or diversion of ground water has been reviewed and evaluated. Two basic types of barriers can be or have been used for ground water control - physical barriers and hydrological barriers.

The physical barriers which are applicable to ground water containment or diversion include slurry-trenches, grout curtains, Imper-walls and sheet pilings. Slurry-trench technology has been available since the 1940's. Slurry-trenching is widely employed in the construction industry, and several firms in the U.S. have considerable experience in slurry-trench construction. The construction requires no elaborate equipment and is relatively straight-forward. Two types of slurry-trenches are common: soil-bentonite and cement-bentonite. The selection of one type of material over another is dependent on the chemical constituents of the ground water and the load bearing needs of the wall. Slurry-trenches have been successfully employed in pollution control. Slurry-trench construction of a 1067 m x 8.2 m barrier from either cement-bentonite or chemically resistant soil-bentonite is estimated to cost $662,000 in 1980 dollars.

Grout curtains are formed by permeation grouting. This procedure is expensive and its applicability is very site dependent. Permeation grouting is only applicable to solids with a permeability of greater than 10^{-5} cm/sec. Only low viscosity grouts must be used if permeability is less than 10^{-3} cm/sec. Permeation grouting is a well-established technology in the construction industry. Several U.S. contractors have the equipment and technical expertise to perform permeation grouting. A wide variety of grouting materials are available to meet most application problems, however, many of these materials are very expensive. No techniques for assessing the integrity of the grout curtain from the ground surface are currently available. This difficulty combined with the very high cost of grout curtain construction and materials($378,000 - $2,953,500) make them an unattractive alternative for pollution control.

The construction industry has used sheet pilings for ground water cutoff for many years, and their installation technology is well developed. In general, the piling have shown little tendency to corrode. However, sheet pilings have not been used in pollution control, and the ability to withstand various pollutants is questionable. Due to tolerances in the manufacture of the sheets, some leakage will occur. The costs for a 1067 m x 8.2 m wall are $725,000 - $1,230,000, which is higher than the proven techniques.

A variation on the grout curtain called Imper-wall or thin wall is also available. In construction of this wall, I-shaped steel forms are driven into the ground. The hole is grouted while the form is removed. Various grouts, including cement, can be used with the costs varying according to the price of the grout. The wall formed by this method is 2.5 - 7.5 cm thick and continuous. The construction method also densifies the surrounding soil which lowers water permeability. Costs for this type of barrier are $301,500 - $431,600 for a 1067 m x 8.2 m wall.

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Hydrological barriers include French drains, wellpoints, and pump-back wells. French drains are essentially trenches containing drain tile, riser pipe and a pump. The trenches are filled with a permeable material. The intercepted ground water flows into the trench and is pumped to the surface. A synthetic liner may be placed along the downgradient side of the trench to stop water penetration. These trenches work well if the aquifer is not too deep and special trenching operations are not required. French drains of 1067 m long and 8.2 m deep cost approximately $304,735 - $318,728.

Wellpoints are the least expensive of all ground water barriers to install. Capital costs for a wellpoint system to cover 1067 m are estimated at $44,494-88,213. This system includes 711 points with each point 8.2 m deep. The points are located at center-to-center distances of 1-1.5 meters due to their small cones of depression. The points are connected to common suction headers which are excavated with centrifugal pumps. Wellpoints can only be used at shallow depths less than 9.2 m. They have been successfully used in pollution control. However wellpoints have significant operating costs due to electricity and maintenance.

Pump-back or deep wells have also been successfully used in pollution control. These wells are used when dewatering at depths greater than 9.2 m. The wells are located so that their cones of depression overlap. A 1067 m pump-back well barrier requires $237,510 in installation costs. Annual operating costs are approximately the same as for wellpoints. If recharge of the aquifer is necessary, other problems arise. Additional costs are incurred for the recharge wells and treatment of contaminated water if necessary. A situation may also occur in which the pump-back wells "leak" or will draw excess clean water from the downgradient.

The capital costs for the various ground water barriers increase in the following order:

wellpoints < pump-back well < French drains < Imper-wall < slurry-trench < sheet piling < grout curtains

Of these techniques, the wellpoints, pump-back walls, Imper-wall and slurry-trenches are proven technology for pollution control. It must be remembered that any ground water barrier has to be designed to meet the objectives and the geohydrology of a particular site. Thus, all barriers may not be applicable to a particular site and costs may vary significantly from our typical site.

In summary, ground water barriers can provide reduced water flow through the area. However, no barrier is totally impermeable, no barrier will last forever and barriers will not usually solve the source pollution problem. Therefore, the questions which must be asked before any ground water barrier for pollution control is installed are: Is the technology available to clean up the pollutant source and is it cheaper to clean up the source now or later?

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I. INTRODUCTION

A.   Objective

The objective of this report is to provide the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) with the current state-of-the-art technology and developmental efforts on methods to contain or divert ground water. These ground water cutoff barriers may be used 1) for diverting the ground water around a lagoon or landfill to control leaching, 2) to completely isolate a lagoon or landfill by placing a continuous wall around the site or 3) to contain a contaminated ground water plume so that the water can be pumped and treated. Types of ground water containment or diversion barriers discussed in this report include 1) slurry-trench cutoff wall, 2) grout-curtain cutoff wall, 3) sheet piling cutoff wall, 4) synthetic membrane cutoff wall, 5) well points, and 6) pump-back wells.

B.   Background

Ground water supplies a major portion of the drinking water in the United States, thus, it is one of the nation's most valuable resources. The abundance of ground water in most parts of the United States has lead to a *laissez faire* attitude toward protection of this resource by both the government and the general public. This attitude is slowly changing, mainly due to increased news media publicity and documented cases of well closings as a result of toxic chemicals in the water. For example, a recent report by the U.S. Senate Committee on Environment and Public Works (1980) lists approximately 1360 well closings from toxic contamination over the period from 1950 to 1979.

In recognition of the need for protection of our ground water resources, EPA is currently developing a ground water protection strategy. This strategy is being developed in three phases. In the completed phase I, information was compiled on water use, contamination, federal and state laws and programs and the state-of-the-art in ground water protection. Phase II consisted of workshops to analyze the issues and recommend alternative policies. These workshops were held in June, 1980.

Phase III will define the strategy for approaching the ground water problem This strategy (to be published approximately January, 1981) will contain the following (Josephson, 1980):

-    a clear statement of problems and issues being addressed,
     with a greater national understanding of ground water
     issues

-    a national program with fully defined federal and state
     roles

-    a comprehensive EPA policy to apply to all programs
     concerned with ground water

- tighter relationships among cognizant federal, state and local government bodies

- a short-term action plan, as well as plans for dealing with ground water problems over the long term.

The contamination of ground water resources arises from several sources including spills, runoff of industrial wastes and leaching of wastes from disposal sites. Of these potential sources of ground water contamination, leachates from waste disposal sites are currently receiving a high degree of news coverage. The Army's Rocky Mountain Arsenal is one of the more widely publicized waste dumps with leaching and ground water contamination problems. The available alternatives for barriers to contain and divert ground water at sites like Rocky Mountain Arsenal are the subjects of this report.

II. PRELIMINARY CONSIDERATIONS FOR INSTALLATION OF A GROUND WATER CONTAINMENT OR DIVERSION BARRIER

The main reasons for installation of ground water containment or diversion barriers are 1) to contain a contaminated ground water plume so as to prevent toxic chemicals from reaching wells or surface waters, 2) to prevent the flow of ground water into a lagoon or landfill or 3) to contain leachate from a lagoon or landfill. However, before any remedial action can be even considered, the geohydrological characteristics of the area must be carefully studied and mapped.

The subterranean surface is a complex interaction of water-bearing formations as shown in Figure 1. The rock and soil which make up the surface and subsurface layers contain water in pores and empty spaces between them. The water content of the subsurface soil increases with depth until all the voids are completely filled with water (saturated zone). In the upper layers (called the unsaturated, retention or aeration zone), the water is adsorbed on the surface of the soil and the empty spaces are filled with freely circulating air. The water phase in this layer has a pressure which is less than atmospheric and water flow is through capillary action.

In the saturated zone, all the pores and voids are filled with water. The water pressure in this zone increases with depth. The depth where the water pressure is equal to the atmospheric pressure defines the water table or piezometric surface and the upper limit of the aquifer or ground water. A capillary fringe of the saturated zone is located above the water table. This fringe of water is maintained by the capillary suction of water from the aquifier. The thickness of the fringe is characterized by the size of the voids in the soil, with the smaller voids yielding the largest capillary rise. The aquifer may be unconfined or confined. An unconfined aquifer is in direct contact with the atmosphere via pores or voids in the overlying soil. The confined aquifer has no direct contact with the atmosphere due to an overlying impermeable stratum called the aquiclude.

The aquifer acts both as a storage and transport medium for water. The storage capacity of the aquifier is measured by the porosite of its stratum. Porosity ϕ is defined as void volume/total volume. The transport or water-carrying ability of the aquifier is determined by its permeability which is a function of average pore size and shape, orientation, and degree of cementation of the grains.

Ground water normally flows under the influence of gravitational forces, however, the velocity of flow varies greatly depending on porosity and hydrodynamic gradients. The natural hydrodynamic flow of ground water can be significantly disturbed by the presence of wells. When a well is pumped, there is an outflow of water from the well which, if pumping is not too great, will eventually reach an equilibrium with the inflow from the aquifer. This phenomenon influences the shape of the water table surface to form a cone of depression extending out some distance from the bore hole as shown in Figure 2. Water located in this zone of influence will tend to migrate towards the bore hole. Thus, a well can be contaminated by a ground water plume located some distance away as shown in Figure 3.
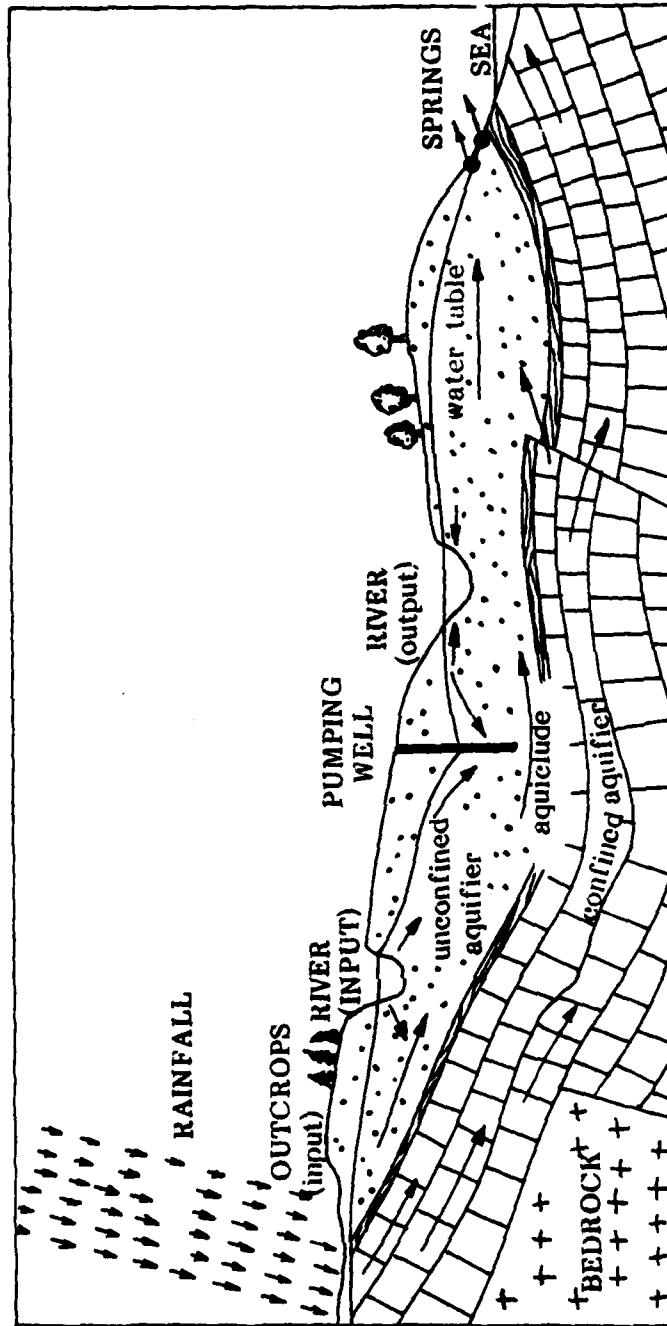
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(de Pastrovich *et al.*, 1979)
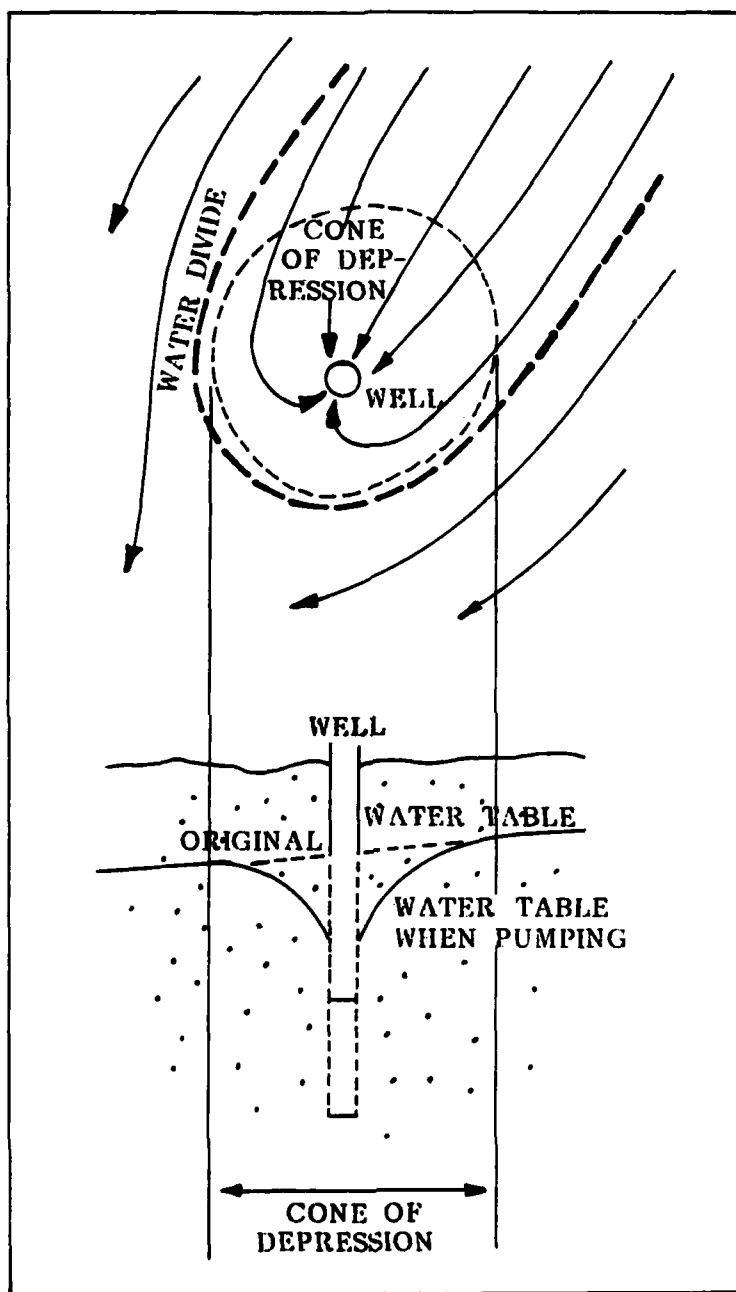
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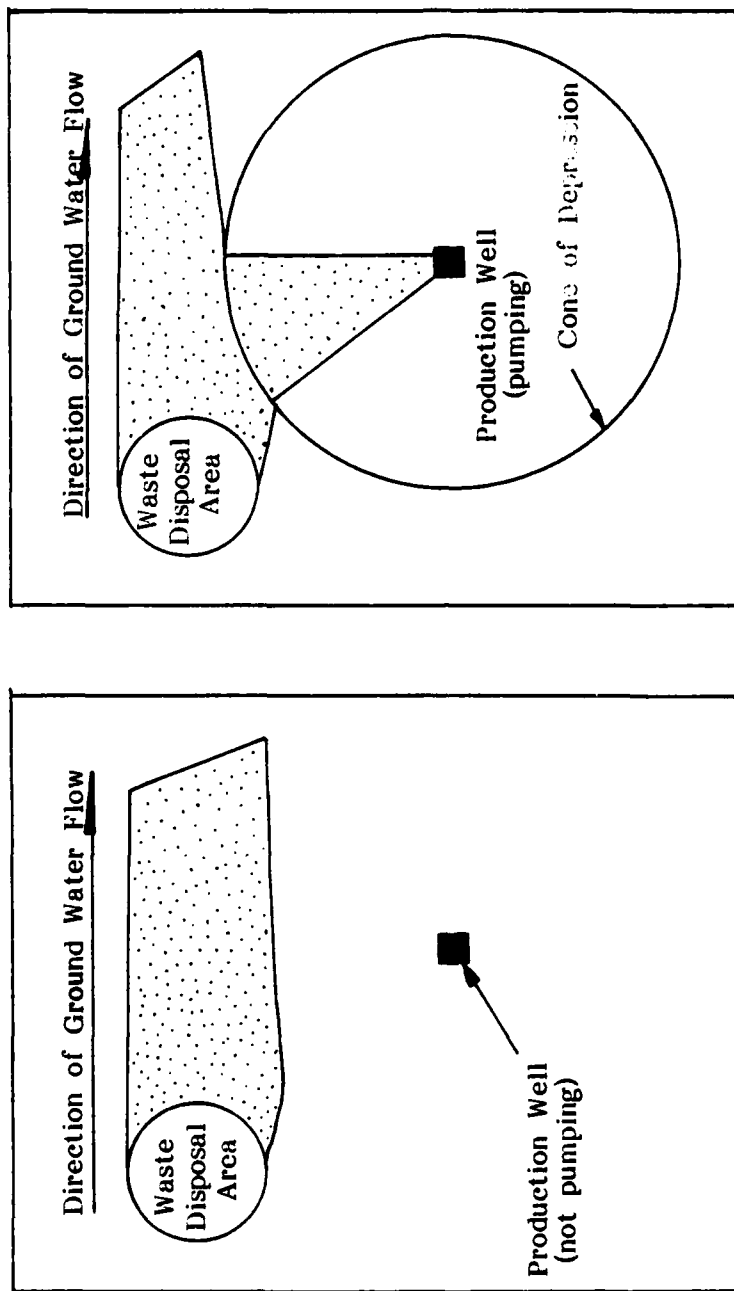
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The complexities of ground water remedial action require that some of the basic geohydrological parameters of the area of concern be known. Technical data required includes:

- nature of subsurface soil

- aquifer characteristics

- depth of ground water surface

- velocity and direction of ground water flow

- location of water extraction wells

- size and shape of contaminated plume

- concentrations of toxic materials in plume

- dilution or adsorption characteristics of the aquifer

- solubility characteristics of the toxic materials in the ground water

The information needed to assess the severity of the problem and the applicability of potential solutions can be obtained by an experienced geohydrology firm. Usually this task involves a number of field measurements followed by input of the data into a mathematical model which can predict the behavior of the aquifer. To collect the data needed for input to the model, test or observation wells are drilled to measure the piezometric levels and construct a piezometric map of the aquifer. Well capacities can be used to derive local flow velocities. Tracers can also be used to measure flow velocities and rates of dilution between wells. Chemical analysis of samples from the observation wells will provide concentrations of the chemical as a function of distance from the polluting source.

Once the geohydrology of the area and the extent of the toxic plume are known, then a logical decision can be made as to what types of barriers are technically feasible for the area. Capital and operating costs, and political considerations can then be employed to further select the appropriate barrier for the contaminated area. Types of barriers available, the methods of construction, past applications of the barrier, costs of construction, advantages and disadvantages and the type of contamination for which the barriers have been used are discussed in the following sections. The cost data presented are for the construction, maintenance and operation of the barrier only. Other costs which are site dependent or dependent on the specific use of the barrier are not included.

III. SLURRY-TRENCH CUTOFF WALL

A. Background

A slurry-trench cutoff wall is an underground wall composed of bentonite clay slurry mixed with an appropriate filler such as soil or cement. The wall is relatively impervious to water, and is intended to prevent ground water flow across the barrier. Such walls are also used to prevent recycling of clean water into a system of recharge wells and to provide storage capacity in the ground when such wells are shut down.

Slurry-trench technology is a direct outgrowtn of the use of mud slurries to stabilize the sides of holes during drilling. While there is some disagreement concerning where and by whom the first slurry wall was built, it is generally agreed that this technique was first applied in 1948. Xanthakos (1979) reports that the first slurry-trench cutoff wall was probably built at Terminal Island near Long Beach, California. The wall was constructed of earth mixed with bentonite slurry, and was 45 feet deep. Impresa di Castruzioni Opere Specialiyzate Company (I.C.O.S.) of Milan, Italy, also claims to have built the first slurry wall. This slurry wall was used in the construction of the Milan subway in 1948 (Tamaro, 1976; I.C.O.S., 1979). Early patents for slurry wall construction techniques and subsequent development work helped I.C.O.S. dominate the field for some time. The technique has found numerous markets and applications. Slurry wall technology is widely known and well-accepted in Europe, Japan, and North and South America (I.C.O.S., 1979).

B. General Description

Ground water contamination from landfills and waste lagoons is the result of surface and ground water seepage into the contaminated area and subsequent leaching of material into the local aquifer. The purpose of a slurry-trench cutoff wall is to present an impervious barrier to ground water, diverting the flow around the contaminated site (Figure 4), to contain contaminated leachate (Figure 5) or to contain a contaminated ground water plume for treatment (Figure 6). Most slurry walls are keyed into an impervious layer of clay or rock, preventing nearly all ground water flow through the site. Those which do not extend all the way to the impervious layer have the effect of lowering the water table so that ground water flows under, but does not interact with, materials in the site.

Construction of a slurry-trench cutoff wall is straightforward and relatively inexpensive compared to other ground water control techniques. A trench as wide as the finished wall is dug to the full depth of the wall. A sodium bentonite and water slurry is added to keep the trench full as the digging progresses. The bentonite slurry has three major functions in the trenching process. First, it stabilizes the sides of the slurry-trench, preventing soil from sloughing-off and preventing ground water from flowing in. Second, it must be workable enough to permit the excavation equipment to pass through it easily. Third, it must form an impermeable barrier on the sides of the trench to prevent the slurry from leaking out during construction (Ryan, 1977). The unique properties of sodium bentonite, which will be discussed in a later section, make the material ideally suited to this application.

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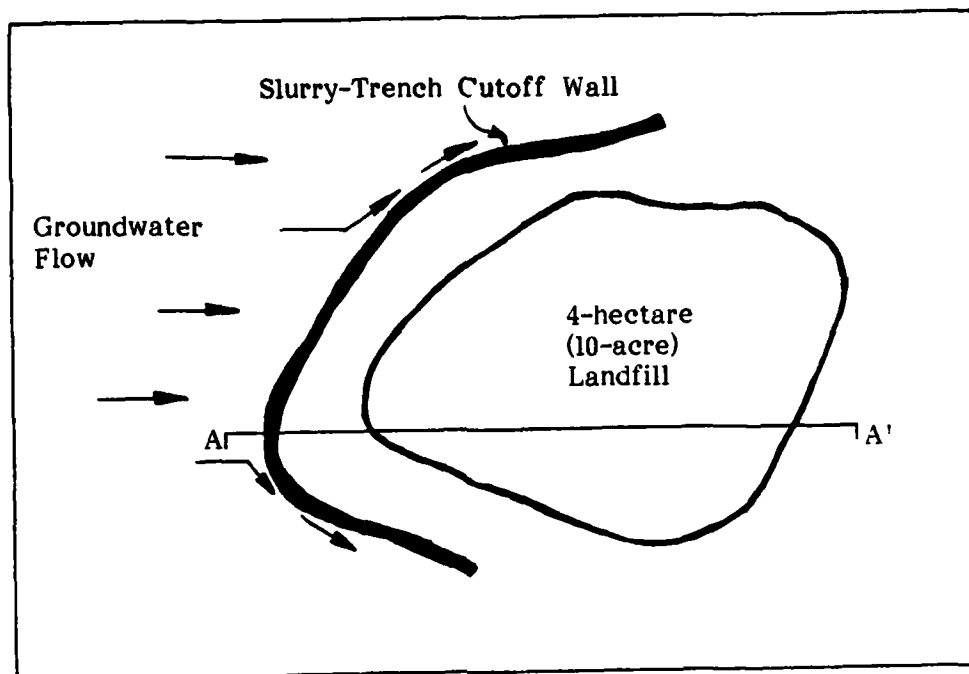
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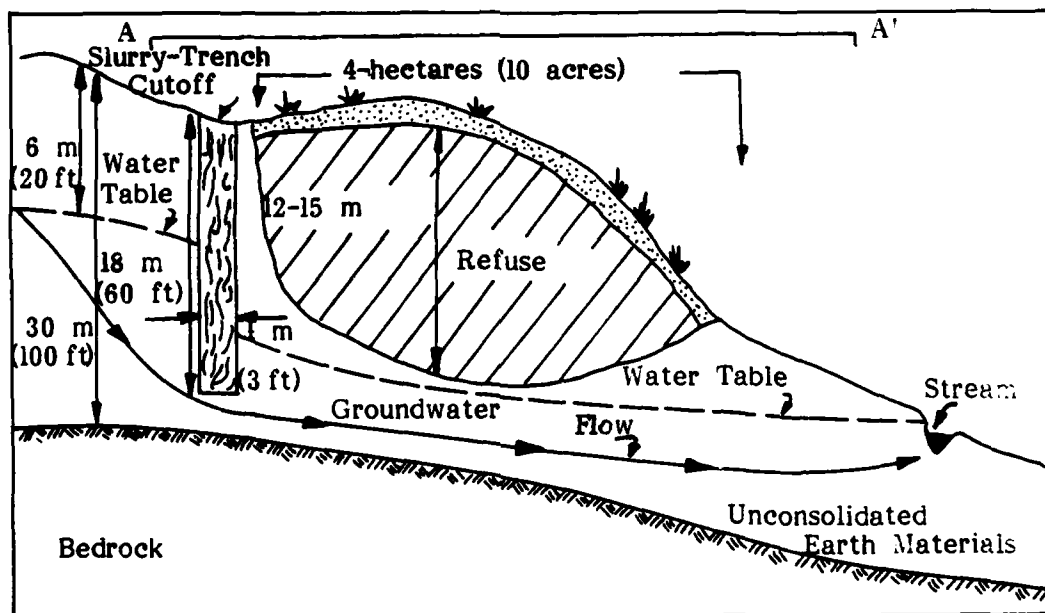
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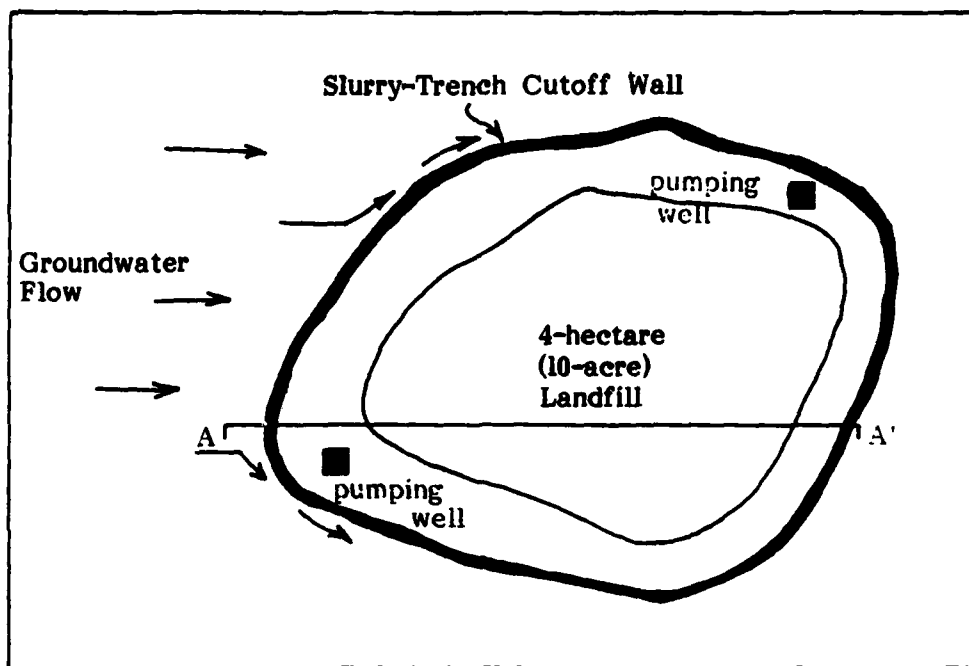
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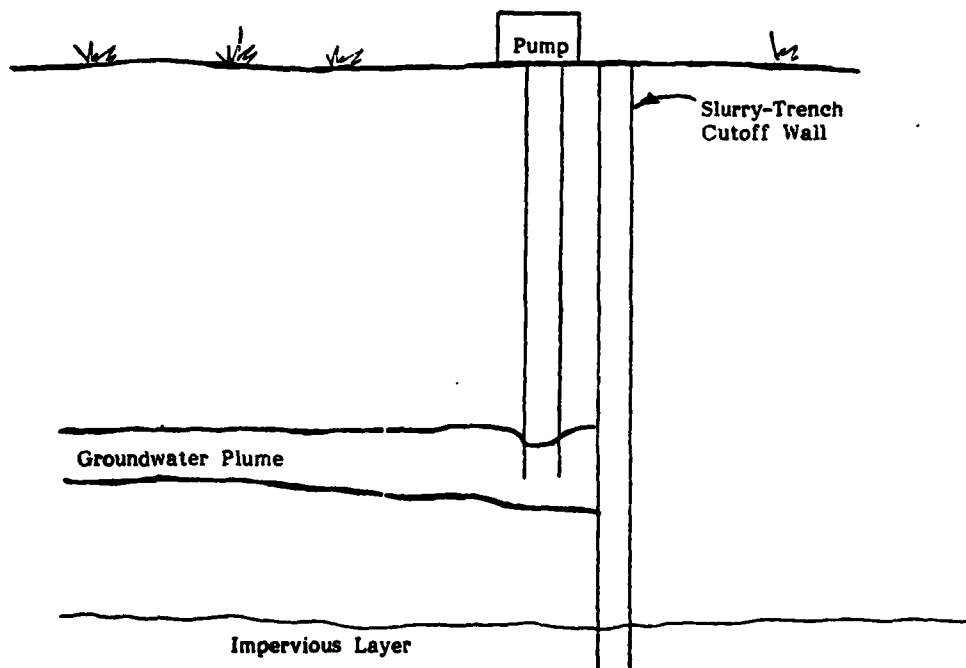
Figure 6.   Cross Section of Slurry-Trench Cutoff Wall for Containment
            of a Contaminated Ground Water Plume

Two types of slurry-trench cutoff walls are in common use: the soil-bentonite cutoff wall and the cement-bentonite cutoff wall. The soil-bentonite (SB) or American method uses soil, often removed from the trench as part of the backfill material. For this type of trench, the soil is mixed with the bentonite slurry to make the fill material. When the trench has been dug to a length of about twice its depth, the backfilling operation begins. The soil-bentonite mixture is gently lowered or pushed into the trench to form the final wall, as shown in Figure 7. The trenching, backfill mixing, and backfilling operations proceed simultaneously until the wall is complete. The resulting SB cutoff wall is flexible and relatively impervious to water.

A cement-bentonite (CB) or European method cutoff wall differs from a soil-bentonite wall in that there is no backfilling process. Cement is mixed with the sodium bentonite slurry and this mixture is used to stabilize the trench. Excavation is performed through the slurry as before, with additional slurry added as needed to keep the trench full. The cement bentonite mixture sets up to the consistency of lard in approximately 12 hours. The CB material keys well into itself, thus, even if the material sets up overnight, trenching can resume the next day by either digging through part of the CB mixture or starting in the adjacent dirt. When the excavation is complete, the cement-bentonite mixture forms an impermeable barrier to ground water. The CB barrier is less flexible but has greater load bearing capacity than the SB barrier.

C.   Materials

Sodium bentonite is a naturally occurring clay found in Wyoming, Montana and South Dakota in the United States. It is an aluminum silicate known as montmorillonite and was formed millions of years ago from volcanic ash and sea water. The mineral has an unusual platelet structure which causes it to swell when contacted with water. Bentonite absorbs six to eight times its own weight in water and swells to ten to twenty times its original dry volume (Hughes, 1976). This remarkable phenomenon leads to the unique properties cited earlier which make bentonite so well-suited to slurry trenching. A bentonite-water slurry is highly thixotropic, allowing excavation equipment to move through it easily, but providing adequate support for vertical trench walls. Any soil knocked loose in the trenching process remains suspended in the slurry rather than settling to the bottom of the trench where it could interfere with the seal to an impervious layer. Another important effect of the platelet structure of bentonite is the formation of a filter cake on the trench walls. The slurry seeps into the walls of the trench, depositing bentonite in the soil voids. As more water seeps out, a thick film of bentonite builds up rapidly to form a watertight seal. The remaining slurry is trapped in the trench, exerting enough hydrostatic pressure to prevent ground water leakage into the trench.

Water impurities can have serious effects on the properties of the bentonite slurry. The presence of any agent which interferes with the swelling of the bentonite requires that larger amounts of bentonite be added to obtain a slurry of the desired viscosity. Field data indicate that the final properties of the slurry wall are not very sensitive to impurities if a slurry of the specified viscosity and density is used (Ryan, 1977), but bentonite consumption may increase substantially. In high enough

BACKHOE
KEYS TRENCH
INTO
CLAY LAYER

▽ G.W.L.

SLURRY LEVEL

BENTONITE SLURRY

BACKFILL
SLOUGHS
FORWARD

CLAY

100 FT.
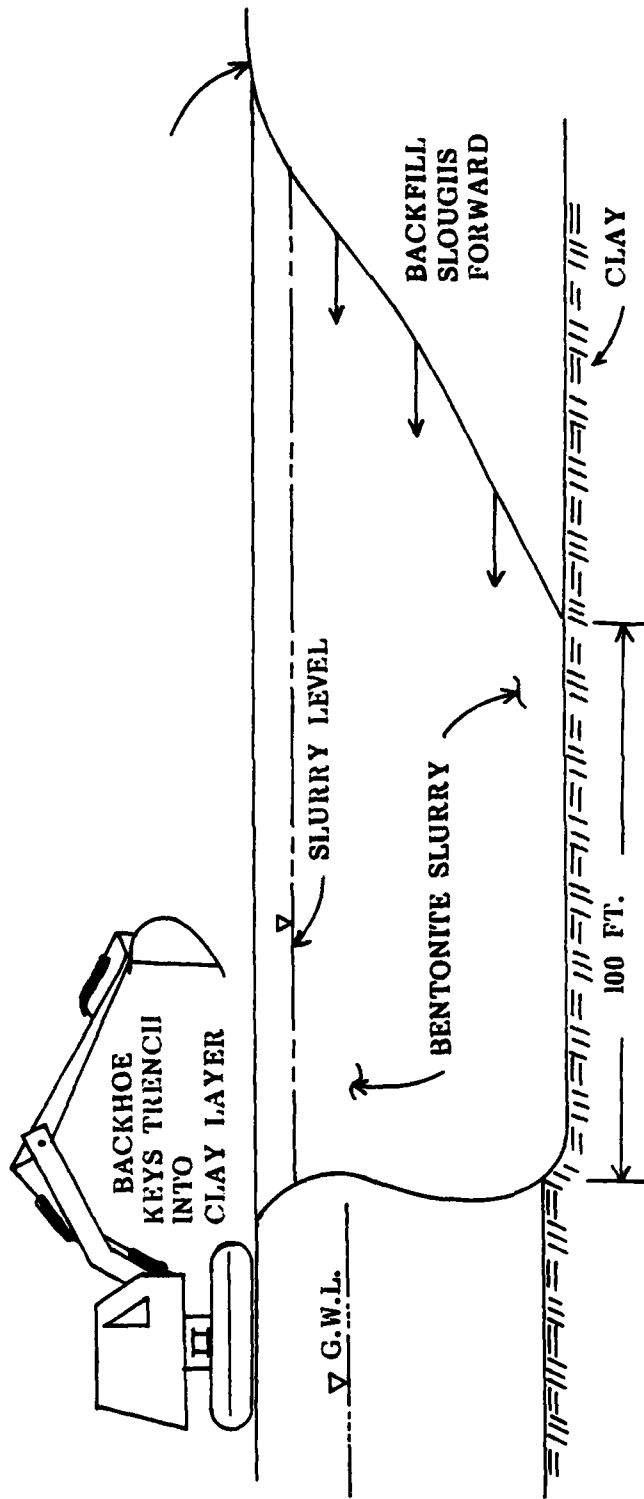
Figure 7. Construction of a Bentonite Slurry-Trench Cutoff Wall (Ryan, 1980)

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concentrations, some impurities will prevent gel formation altogether. Sodium chloride at concentrations greater than 500 mg/l is likely to reduce the swelling ability of the bentonite, producing a lower viscosity slurry (Xanthakos, 1979). Calcium salts at concentrations greater than 100 mg/l (Xanthakos, 1979) interfere with the hydration by replacing sodium bentonite with calcium bentonite which does not swell (Hughes, 1976). According to Xanthakos (1979), water mixed with bentonite should be "clean, fresh, free from oil, acid, alkali, and organic matter."

Once the slurry wall is in place, it is subject to attack by the same impurities as before, however, a number of bentonite additives have been developed which help resist such attacks. One type of additive is simply sodium carbonate which minimizes the effects of calcium, iron and magnesium ions in hard water (Hughes, 1976). The other major type of additive consists of a number of wetting or peptizing agents; polymers are added to improve the swelling properties of the bentonite. Such additives can dramatically reduce bentonite consumption and improve resistance to chemical attack. A number of American Colloid Company bentonite products along with applications and conditions under which they may be used are listed in Table I.

For soil-bentonite cutoff walls, the soil aggregate can range from well-graded gravel to poorly graded medium-fine sand (Ryan, 1977). An ideal backfill material consists of well-graded sand with 10-30% fines (Ryan, 1977); in most cases, soil dug from the trench is acceptable. In the construction of cement-bentonite walls, Portland cement is usually used because of its wide availability in the U.S. (Ryan, 1977).

D.   Construction

Slurry-trench depth is usually determined by the depth to an impervious layer of rock or clay below the aquifer. If the slurry-trench is to prevent landfill or lagoon leaching, the length of the wall is determined on the basis of the size of the contaminated area and the desirability of completely surrounding it. In most cases, it is sufficient to partially surround the area upstream of the contaminated region. For cutoff of a contaminated ground water plume, the width of the plume determines the length of the wall. In general, the wall thickness should be approximately one foot for every ten feet of hydrostatic head, however, the thickness can be increased to further reduce seepage across the wall.

The type of equipment used for digging the trench is dictated by the thickness of the wall and by the required depth. The hydraulic excavator or backhoe is the most economical and efficient piece of equipment for trench digging (Ryan, 1976). Minimum trench width is determined by boom thickness, while the maximum depth is 10.7 - 12.2 m. For depths up to 36.5 m, draglines provide the least expensive method of excavation. Minimum bucket widths are in the 1.5 - 2.44 m range, which may be prohibitively expensive in terms of material costs for cement-bentonite slurries (Ryan, 1976). For still deeper excavations, clamshell bucket rigs must be used. With a maximum depth of 76.2 m and a minimum bucket width of .46 m, this equipment leads to higher trenching costs due to its much slower excavation rate (Ryan, 1976).

Table I. Product Listing for Volclay Sealants Seepage Control Systems
(Environmental Products Division, American Colloid Co., 1978)

Conditions	Product	Product Description
Lagoons, Ponds, Dams		
Water with less than 1000 ppm TDS*	SG-40	Highest Efficiency - low tolerance for contamination
Water with TDS between 1000 and 10,000 ppm	PLS-50	High Efficiency - medium tolerance for contamination
Water with TDS in excess of 10,000 ppm	Saline Seal 100	Contaminant resistant soil sealant will resist contamination in excess of 100,000 ppm TDS
Sanitary Landfills		
Hazardous Industrial Wastes	SLS-70	Will contain highly contaminated leachate
Municipal Waste Only	SLS-71	High Efficiency Sealant - will contain leachate from municipal waste - but not industrial waste
Tank Farms		
Chemical Storage - Inorganic	TFS-80	Will contain spills of strong inorganic chemicals
Crude Petroleum or other organics contaminated with inorganics	TFS-81	High Efficiency Soil Sealant - will contain spills of organic contaminated with mild inorganic or subject to inorganic contamination such as Sea Spray
Cutoff Walls		

The selection of Volclay products for cutoff walls is dependent upon soil, water and liquid contaminant conditions.

Each case should be studied separately.

* TDS - Total Dissolved Salts

There are several properties which should be controlled when mixing the bentonite slurry. First, the bentonite should be completely hydrated before being poured into the trench or mixed with soil in the case of a soil-bentonite slurry wall, and before being mixed with cement in the case of a cement-bentonite slurry wall. Hydration times are typically much shorter for peptized bentonite (Ryan, 1976). Second, the slurry must be within the specified viscosity limits. If the viscosity is too low, the trench will collapse; if it is too high, excavation becomes difficult and large lumps of porous soil may remain suspended and form permeable channels in the finished wall (Ryan, 1976). Viscosity as measured by the length of time required for a specific volume of slurry to pass through a Marsh funnel can range from 35 to 80 seconds; ideal values are 40-45 seconds (Ryan, 1976). Third, the slurry density for a soil-bentonite wall must be significantly less than that of the soil backfill mixture. If the density is too great, the backfill will not displace the slurry, leaving pockets of slurry in the finished wall (Ryan, 1976). Density is not as critical for a cement-bentonite slurry wall, since there is no backfilling process.

Hydration rate varies with the quality of the bentonite, the presence of peptizing agents, and the mixing method used (Ryan, 1976). There are essentially two types of mixing systems. The first method utilizes high speed agitation by circulation pumps or by a high shear paddle mixer. While hydration time is short, possibly as short as several minutes for a high quality peptized bentonite, the total output of this mixer is relatively low (Ryan, 1977). The second type is a flash or venturi mixer which subjects the bentonite to very high shear forces produced by water jets for a fraction of a second. Although complete hydration requires storage for several hours in a circulating pond, this method is preferred at large sites for its high productivity, up to 25 tons/hr (Ryan, 1977).

For cement-bentonite slurry walls, the cement is weighed and mixed with the bentonite slurry as it is placed in the trench (Ryan, 1976), usually around 1920 kg/m^3 (Ryan, 1977). The cement-bentonite mixture begins to set after a few hours, can be walked on by the second day, and achieves its final set within 90 days (Ryan, 1977).

For soil-bentonite slurry walls, the soil-slurry mixture is worked to a smooth consistency by a bulldozer. Approximate proportions are determined by a slump cone test which should give a reading of approximately 7.6 cm (I.C.O.S., 1979). The slurry-soil mixture is either gently pushed or bulldozed or gently lowered by excavation equipment along an angle of repose of 6 to 8 horizontal to 1 vertical (Xanthakos, 1979). Backfill should not be dropped into the trench, since this would deposit coarse soil on the bottom and maintain only the fine fraction in suspension. Such sudden backfill addition could also trap slurry pockets in the finished wall. Since the soil-bentonite mixture does not set, the cutoff wall is complete as soon as the backfilling operation is finished.

E.   Performance

Coefficients of permeability for both CB and SB slurry-trench walls are on the order of 10^{-6} cm/sec. This coefficient, k, is defined by the ASTM Procedures for Testing Soils (1964) as the "rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit

hydraulic gradient and standard temperature conditions (usually 20°C)." This information can be used with Darcy's equation for laminar flow through porous media to calculate the expected fluid loss from an uninterrupted slurry-trench cutoff wall. For water at 20°C:

$$v = ki$$

v is the discharge rate, cm/sec

k is the coefficient of permeability, cm/sec

i is the hydraulic gradient, cm liq/cm wall

A 0.5 m thick wall with a permeability of 10^{-6} cm/sec under a hydrostatic pressure of 10 m of water allows ground water to flow through at the following rate:

$$v = (10^{-6} \text{ cm/sec}) \frac{(1000 \text{ cm})}{50 \text{ cm}}$$

$$v = 2.0 \times 10^{-5} \text{ ml/cm}^2 \cdot \text{sec}$$

$$v = 0.72 \text{ l/m}^2 \cdot \text{hr}$$

This is the maximum flow rate through the base of the wall where hydrostatic pressure is greatest. The slurry wall can be made more watertight by building a thicker wall or by decreasing the permeability of the wall materials. For a soil-bentonite wall, increasing the amount of bentonite slurry added to the backfill decreases the permeability. For a cement-bentonite wall, permeability is dependent on the cement to water and the cement to bentonite ratios.

Although cement-bentonite walls are somewhat more rigid than soil-bentonite walls, both types are flexible enough to withstand, without cracking, any deformation they might encounter under typical loading conditions (Ryan, 1977). While minor cracks in a soil-bentonite slurry wall would tend to seal themselves, failure of a large section of the wall would be very difficult to repair. The soil-bentonite mixture would tend to slide into any re-excavation, requiring that a long section of the trench be dug out and rebuilt. For failure-prone areas, cement-bentonite walls should be used (Ryan, 1977). Failure of a cement-bentonite slurry wall would actually stabilize the surrounding soil, making it fairly easy to excavate that section of trench (Ryan, 1977). New cement-bentonite slurry added to the trench seals well to pre-existing segments, making it possible to build the wall in sections as well as repair any damaged areas. According to Ryan (1977), there have been no reported failures of slurry-trench cutoff walls in the United States.

A slurry-trench cutoff wall which is intended to protect ground water from contaminated leachates or to contain a contaminated ground water plume must be resistant to the anticipated contaminants. Portland cement is particularly susceptible to attack by sulfates, by sea water and by acidic wastes (Neville, 1975). At sites where these contaminants are anticipated in significant amounts, cement-bentonite

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slurry walls should not be built. As previously mentioned, sodium bentonite is vulnerable to attack by sodium chloride, calcium salts, oils and some organic contaminants. While specially treated bentonites have been developed to overcome these problems, permeability tests over a period of one or two months should be performed on a small scale before using any bentonite product on a new contaminant or a new combination of wastes (Cosgrove, 1980).

Some specific situations to which slurry-trench cutoff wall techniques have been applied are listed in Table II. A brief list of some contractors with slurry-trench experience is given in Table III.

F.   Application to Rocky Mountain Arsenal

In order to have a consistent basis for comparison of the various ground water control techniques, each technique will be applied to the problem of intercepting ground water flow through the northern boundary of Rocky Mountain Arsenal. Hydrogeologic data for the area were taken from the Battelle report, "Study of Alternatives for Groundwater Pollution Control at North Boundary of Rocky Mountain Arsenal" (Thomas et al., 1979) and from the A.D. Little report, "State-of-the-Art Survey of Land Reclamation Technology" (Berkowitz et al., 1976). Permeability for the area is reported to be 37 to 70 m/day or 4.2×10^{-2} to 8.1×10^{-2} cm/sec. Thomas estimates a peak flow of 37,800 l/hr across a 427 m length of the northern boundary. According to Berkowitz, the soil is a mix of sands, silts and clays, with sand lenses throughout   silty regions accounting for much of the ground water flow. For comparison, all cutoff techniques will cover a region 1067 m long and 8.2 m deep. These are the dimensions recommended by Thomas for a slurry-trench cutoff wall, and they will be used throughout this report.

In view of the wide variety of organic and inorganic contaminants at Rocky Mountain Arsenal, a high quality chemical resistant bentonite will be required. Cost estimates are presented for both a soil-bentonite and a cement-bentonite wall. An evaluation of performance for both types of material in contact with actual Rocky Mountain Arsenaal wastes will be required before a final choice could be made.

G.   Economics

The most important cost factors in slurry wall construction are slurry materials, wall surface, and required depth. Costs are figured on the basis of square meters or square feet of wall surface (length x depth) because labor and equipment costs for excavation are usually considerably higher than raw material costs.

The raw material costs for a number of bentonite products and for Portland cement are presented in Table IV. In both CB and slurry-trench cutoff walls, shipping costs can represent a significant portion of the purchase cost, particularly for bentonite which must be shipped from Wyoming, Montana or South Dakota. While cement costs are fairly high, cement requirements can be reduced somewhat by the addition of flyash when it is available. Table V lists installed costs for soil-bentonite and cement-bentonite slurry walls. There is generally good agreement, so these

Table II. Slurry-Trench Cutoff Wall Applications

Location	Type of Wall	Application
Columbus, MS	SB	Isolation of sewage effluent ponds
Dubois, PA	SB	Containing of acid mine wastes
Texas	SB	Chemical wastes
Scituate, MA	SB	Sanitary landfill isolation
3M	SB	Sulfuric acid pond, 5% H_2SO_4
St. Gabriel, LA	mixed blanket-soil and bentonite mixture on bottom of pond	Herbicides in pond
Battery Manufacturer, FL	mixed blanket-soil and bentonite mixture on bottom of pond	Nickel in effluent
Bryan Reservoir, LA	SB	Brine storage
Sports Complex, East Rutherford, NJ	SB	Protection of leachate from tidal marshes and abandoned landfills
Cluff Lake, Saskatchewan	SB	Tailing dam for a uranium mine
Kennedy Airport, NY	CB	Prevention of aviation fuel and oil from escaping tank farm into bay and ground water
CF Industries, NC	SB	Contaminated fertilizer wastes high nitrate content
Ft. Edwards, WI	SB	Paper mill sludge pond
Total Oil	CB	Prevention of oil seepage
Phillips Petroleum, TX	CB	Oil leachates
Arcoa, AL	CB	Caustic wastes
Rocky Mountain Arsenal	SB	DIMP, DCCP, inorganics

Table III. U.S. Companies with Slurry-Trench Experience

Geo-Con, Inc.   Over 100 slurry walls designed by top two
P.O. Box 17380   managers
Pittsburgh, PA   15235
(412) 244-8200

Hayward Baker Co.   Just starting to get into slurry wall business.
1875 Mayfield Road   Most experience with diaphragm walls.
Odenton, MD   21113
(301) 551-8200

I.C.O.S. Corporation of America   Large amount of experience in both cement
4 West 58th Street   bentonite and soil-bentonite cutoff walls
New York, New York   10019
(212) 688-9216

W.T. Jaques Company
Des Moines, IA
(515) 276-5464

Slurry System, Inc.   Eight years and 2,400,000 ft^2 SB walls, but
7100 Industrial Avenue   most of their work in CB
Gary, IN   46406
(219) 949-0561

Spencer, White and Prentiss
10 East 40th
New York, New York

Warren-Foncledile, Inc.
675 Massachusetts Avenue
Cambridge, Massachusetts   02139

Table IV. Material Costs for Slurry-Trench Cutoff Walls
(Tolman et al., 1978)

Product	Manufacturer	Purpose	Cost
Saline Seal-100	American Colloid	Salt Water Resistant	$152/ton bulk
PLS-50	American Colloid	High Efficiency	$58/ton bulk
SG-40	American Colloid	General Purpose	$45/ton bulk
Hi-Seal 12-3	Federal Bentonite	Salt Water Resistant	$96/ton bulk ($104/ton in 100 lb bags)
Bentonite	Federal Bentonite	General Purpose	$27/ton bulk ($34/ton in 100 lb bags)
Portland Cement			$36-38/ton
Shipping Cement (100 miles)			$18-28/ton

Table V. Installed Cost of Slurry-Trench Cutoff Walls

Source of Information	Soil-Bentonite		Cement-Bentonite	
	$/m²	$/ft²	$/m²	$/ft²
American Colloid Co. Skokie, IL	32.29	$3	–	–
Geo-Con, Inc. Pittsburgh, PA	32.29-43.06	$3-4	43.06-64.59	$4-6
Slurry System, Inc.	32.29-53.82	$3-5	–	–
I.C.O.S. Corporation of America New York, NY	–	–	53.82-75.35	$5-7
Hayward Baker Odenton, MD	53.82	$5	75.35	$7
Saline Seal-100	75.35	$7	–	–
Depths greater than 40 ft.	107.64-161.46	$10-15	–	–

Depths not specified are assumed to be less than 40 ft.

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numbers are considered fairly reliable. While chemical resistant bentonites and cement-bentonite mixtures raise wall costs somewhat, much greater increases are seen for walls whose depths require the use of slower excavation equipment. At depths of greater than 12.2 m, slurry-trench cutoff walls may be unattractive economically because of the high excavation costs.

A cost breakdown for a soil-bentonite slurry cutoff wall is detailed in Table VI. In this example, bentonite accounts for only 25% of the total installed cost.

A slurry-trench cutoff wall built according to specifications in the Battelle report on Rocky Mountain Arsenal would be 1067 m long and 8.2 m deep. Since chemical resistant soil-bentonite and cement-bentonite walls are estimated to cost around $75.35/m^2, the cost for either a CB or SB wall would be approximately $662,000 in 1980.

H. Advantages and Disadvantages of Slurry-Trench Cutoff Walls

Slurry-trench cutoff walls have certain inherent advantages over other methods of ground water control. Slurry walls achieve positive ground water control without the drawdown in ground water level associated with other methods (Xanthakos, 1979; Ryan, 1976). This is important in some areas where crop damage and settling of existing structures can result from such changes in ground water level. A second major advantage is that slurry walls require no maintenance after installation. Construction methods are simple, relatively cheap, and normally do not require the use of unusual equipment or techniques. Walls can be inserted even into very mobile soils, providing a flexible, impermeable barrier with no seams or joints for potential leakage (Xanthakos, 1979).

There are also drawbacks associated with using slurry walls for ground water cutoff. A slurry wall alone cannot prevent all leaching from a contaminated site or total cutoff of a contaminated plume. While a slurry wall dramatically reduces ground water flow, it is not practical and probably not possible to prevent all seepage across the barrier with this technique. Unless the wall completely surrounds the site, a slurry-trench cutoff wall is most easily built where the depth to an impervious layer is not great. Rocky terrain can also make the excavation difficult. There have been some problems with backhoe excavation caused by silt being drawn into furrows left by the teeth of the backhoe. This can cause "windows" in the bottom of the wall which can allow significant amounts of ground water to flow through (Harmston, 1980).

Soil-bentonite cutoff walls are very economical because of their small material requirements. While natural bentonite is susceptible to several types of chemical attack, numerous additives have been developed which make the wall resistant to a wide variety of chemicals (Tolman et al., 1978). A major advantage of the soil-bentonite wall is that bentonite, being a mineral, does not deteriorate with age (Tolman et al., 1978).

Cement-bentonite cutoff walls have some advantages over soil-bentonite walls, however, they are also considerably more expensive due to the high cost of cement. Cement-bentonite walls are not dependent on the availability or quality of backfill material, and they can be built in confined spaces, such as dams, where there is no room for mixing backfill by the side of the trench (Ryan, 1977). Since the

Table VI. Cost breakdown for a Soil-Bentonite Cutoff Wall for Rocky
Mountain Arsenal (Berkowitz et al., 1976)

Dimensions

    0.8 mi length x 40 ft depth x 5.5 ft thickness

Costs (1980 dollars)

Excavation equipment mobilization	$ 98,000
Excavation of trench with scraper and dragline	214,000
Wyoming bentonite slurry	142,000
Soil backfill into slurry trench	45,000
Site clean-up	27,000
Field investigation and tests	18,000
Engineering and design	53,000
TOTAL	$597,000

$(597,000) \div (0.8 \times 5280 \text{ ft} \times 40 \text{ ft}) = \$3.53/\text{ft}^2$

backfill mixing step is eliminated altogether, labor costs are reduced and there is less mess along the side of the trench when the wall is finished (Ryan, 1977). The cement-bentonite backfill is far more homogeneous than the soil-bentonite backfill. Since it fills the trench completely, there is less chance of trapping permeable pockets, and a thinner cement-bentonite wall is required to assure the same level of permeability (Ryan, 1976).

IV. GROUT CURTAINS

A.   Background

Grouting is the practice of injecting a fluid material into soil, rock or concrete to alter the physical characteristics of the mass so as to reduce water movement or to improve the strength of the formation. This technique has been employed with a variety of grouting materials since the 1800's. The majority of grouting applications have been in the construction industry to prevent shifting of cohesionless soils, water cutoff, stabilization of soils, strengthening of soils or slab leveling. Three major types of grouting techniques are used in the construction industry: 1) permeation grouting, 2) mudjacking and 3) compaction grouting. Permeation grouting involves the filling of small voids in a soil deposit with grout fluid by pressure injection. Any ground water in the soil pores is displaced by the grout fluid. The mudjacking technique uses a heavy grouting material under high pressure to fill the voids under a structure and raise the structure. Compaction is used for consolidation of cohesive soils, such as clays, which are not groutable by permeation techniques. Compaction consists of injecting a viscous grout under high pressure to displace and densify the underlying soil.

B.   Construction Considerations and Limitations

Construction of a grout ground water cutoff barrier, *i.e.* a grout curtain, is accomplished by permeation grouting. The curtain is formed by pressure injection of the grouting material into the ground through a series of injection pipes. These pipes are arranged in a grid pattern to form a solid curtain as shown in Figure 8. Water is prevented from seeping under the curtain by constructing the curtain so that it penetrates into an impervious soil layer.

The applicability of the grout curtain technique to a particular site is determined by the physical and chemical characteristics of the soil and ground water. The success of permeation grouting depends on the ability of the grout materials to flow into the soil pores without fracturing the soil. Thus, grout curtain technology is not applicable to cohesive soils such as clay silts or gumbo. Soil and ground water chemical constituents are also important in determining groutability. Inorganics and organics can react negatively with grouting materials, causing them not to set, to have high permeability or to degrade prematurely. Thus, the first step in grout curtain construction should be a detailed site survey. This survey should include: 1) gathering of geological and geographical data on the site, 2) drilling and sampling and 3) laboratory and field testing of the soil and ground water (Herndon and Lenahan. 1976a).

1.   Site Survey

In the initial stage of the site survey, all the available geographical and geological data on the site should be collected and analyzed.   The   type of information which should be sought should include the following:
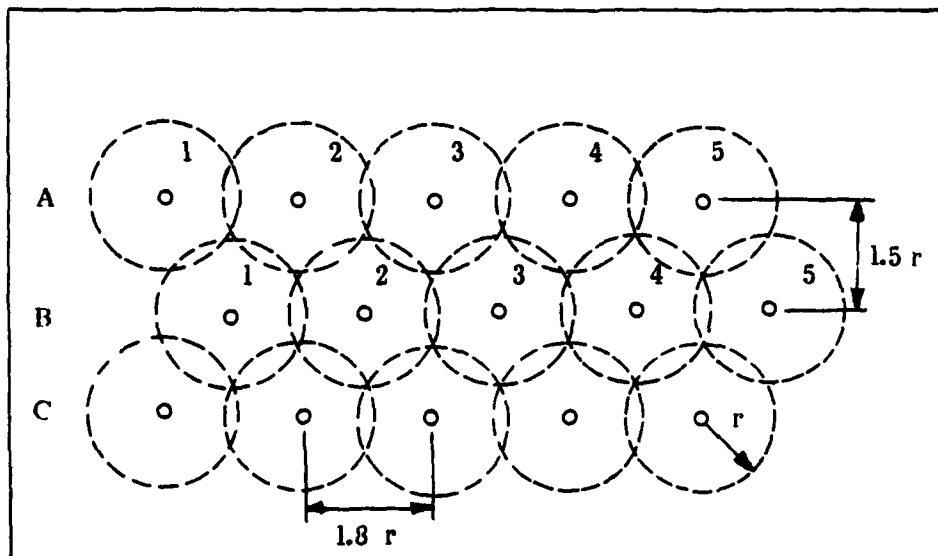
Figure 8a.   Typical Three-row Grid Pattern for Grout Curtain
(Herndon and Lenahan, 1976b).
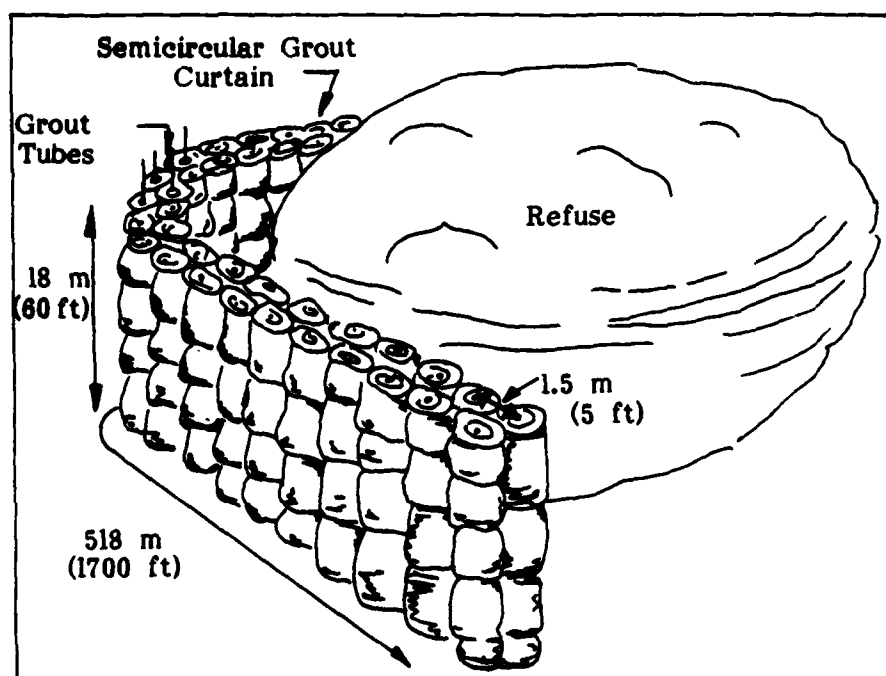
Figure 8b.   Semicircular Grout Curtain Around Upgradient end
of Landfill (Tolman et al., 1978)

- surface topography to determine if grouting can
  be performed from the surface and the best
  location for the equipment

- soil type

- aquiclude type

- location of any subsurface structures, such as
  buried utilities

- water table depth

- location of contaminated plume

- ground water flow rate

- ground water chemical properties

- subsurface soil profiles

Depending on the detail in which previous surveys were conducted, most of the necessary information may be available. Good soil profiles through the area to be grouted are of particular importance to grouting operations. Therefore, information obtained from only a few bore holes cannot be used to design the grouting procedures. Thus, in most instances, drilling of several bore holes across the site and sampling and testing of the soil and water will be necessary to supplement the existing information.

a. Soil Physical Parameters Affecting Groutability

Soil physical characteristics which affect the groutability of a soil include (Herndon and Lenahan, 1976b):

- particle size distribution

- permeability

- porosity

These characteristics can be determined by laboratory tests on core samples retrieved from the bore holes.

The initial determination of groutability is usually based on particle size distribution of the soil (Herndon and Lenahan, 1976a,b). This test is accomplished by passing the dried soil through a series of sieves in accordance with ASTM Method D422. A particle size curve can then be constructed and the effective diameter, D_{10}, determined. This value can be used to roughly estimate the permeability of the soil using Figure 9. In general, a soil is not groutable if more than 20% of the material passes through a #200 sieve. Very low viscosity grouts are required if more than 10% of the soil passes through the #200 sieve (Welsh, 1975).

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Figure 9. Correlations Between Soil Grain Size, Permeability and Potential Dewatering Methods (Herndon and Lenahan, 1976b)

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During the grouting process, the fluid grout must flow into the voids in the soil replacing air or water. Since the permeability is the property which indicates the ability of a fluid to move through a medium, knowledge of soil permeability is necessary for grouting processes. The permeability of the soil not only indicates its groutability, but also the type of applicable grouting material. The coefficient of permeability, k, can be measured either in the laboratory or *in situ.* The laboratory constant head permeability test (ASTM D2434-68) is less expensive than *in situ* testing and is thus used by most investigators. For this procedure, soils collected from the site to be grouted are placed in a permeameter and compacted. The quantity of water that passes through the soil during a given time, while the head is maintained constant, is measured. This procedure is useful for coarse soils with values of k greater than 10^{-4} cm/sec (Herndon and Lenahan, 1976a). For finer soils, a falling head procedure can be used, however, if k is less than 10^{-5} cm/sec, the groutability of the soil is questionable (Herndon and Lenahan, 1976a). The major problem with these laboratory tests is that the compaction and structure of the soil in the permeameter is not the same as in the ground. The *in situ* permeability tests yield more reliable data, however, they are very seldom used by U.S. grouting contractors. Procedures for these tests are detailed in the literature (Herndon and Lenahan, 1976b).

The porosity, n, of the soil is defined as the percentage of void spaces in a given volume of soil. This parameter defines the amount of void space in the soil and thus determines the amount of grout needed to completely fill the voids. Generally, porosity is not measured but is assumed to be approximately 33%.

The pore size distribution could also be measured as an indicator of soil groutability. This determination can be made by injecting mercury into the soil. The pore size can be calculated by measuring the injection pressures required (Herndon and Lenahan, 1976a). However, pore size measurements have not been correlated with groutability.

b.   Ground Water Parameters Affecting Groutability

The flow and chemical composition of the ground water affect the groutability of a particular site and the type of grout that can be used. Ground water flows as low as 1.30 mm/sec have been shown to adversely affect the ability of some grouts to form a solid curtain (Takenaka Komuten Co., Ltd., 1980). If the grout does not set up quickly, the material will be washed away. The result will be a "leaky curtain." Contaminants in the ground water also can affect the ability of some grouts to set and the properties of the grout after gelation.

2.   Selection of a Grouting Material

The successful construction of a grout curtain depends on the selection of the proper grouting material for the specific area to be grouted. Two basic types of grouting materials are available - particulate grouts and chemical grouts. Particulate grouts are non-Newtonian fluids formulated by suspending cement, clay or flyash particles in an aqueous medium. In contrast, chemical grouts are true solutions exhibiting Newtonian flow characteristics. The selection of a particular

type of grout and the specific formulation must be made based on a match of the properties of the grout with those of the soil to be grouted. The properties of a grouting material which influence its application to permeation grouting include 1) viscosity, 2) setting time, 3) stability, 4) water permeability, 5) strength and 6) toxicity.

a.   Grout Viscosity

For permeation grouting operations, the grout selected must penetrate into the soil voids when pumped at a reasonable flow rate and under a pressure less than that required to fracture the formation. The permeation of the grout material into the soil is initially controlled by its viscosity. The viscosity of the grout material is normally a function of the amount of grout formulated into solution. Thus, the grout's viscosity can be altered by changing the formulation as shown in Figure 10. However, as the grout concentration and viscosity are lowered, the strength of the grouted soil is also decreased. Thus, a delicate balance must be achieved between the grout viscosity, flow rate, injection pressure and the required strength of the grouted soil.

The low viscosity grouts (less than 2cP), e.g. many of the chemical grouts, penetrate the soil voids easily and can be used in fine soils having a coefficient of permeability, k, as low as 10^{-5} cm/sec. (Herndon and Lenahan, 1976a,b). High viscosity grouts (greater than 10cP), e.g. particulate grouts and some highly concentrated chemical grout solutions, can only be used in coarse soils with a coefficient of permeability greater than 10^{-2} cm/sec (Herndon and Lenahan, 1976a,b). A further constraint on particulate grouts is particle size. In general, the size of the largest suspended particle should be less than one-third the soil void size (Herndon and Lenahan, 1976a,b).

Once the grout material is mixed, it will begin to set and its viscosity will increase. This increase in viscosity will make injection of the material into the soil increasingly difficult. To compensate for the increased viscosity, a lower flow rate or higher injection pressure must be used.

b.   Grout Setting Time

The setting time of a grout is the amount of time elapsed between mixing of the grout components and the time for formation of a gel for chemical grouts or hardening to the point of immobility for cement grouts. This parameter and changes in viscosity determine the time period during which the grout can be pumped. For particulate grouts, the setting time is a function of the water/particulate ratio and the temperature. As the water/particulate grout ratio is increased, the viscosity, set time and pumpability are increased. Chemical grouts are essentially undergoing a chemical reaction from the time the components are mixed to the time of the final set. These chemical reactions are dependent on temperature, amount of catalyst and accelerator addition (Herndon and Lenahan, 1976a,b). For a one solution chemical grout process, the setting time must be of sufficient duration to allow the grout to be pumped into the soil. Thus, the grout formulation and viscosity and the permeability of the soil must be carefully considered to insure that the grout material will be pumpeable for the length of time required to inject it into the desired area. In a two-shot (Joosten) process, instantaneous setting can be accomplished when the two component solutions of the grout meet. Rapid setting can also be accomplished with grouts that react with the ground water or ground water constituents.
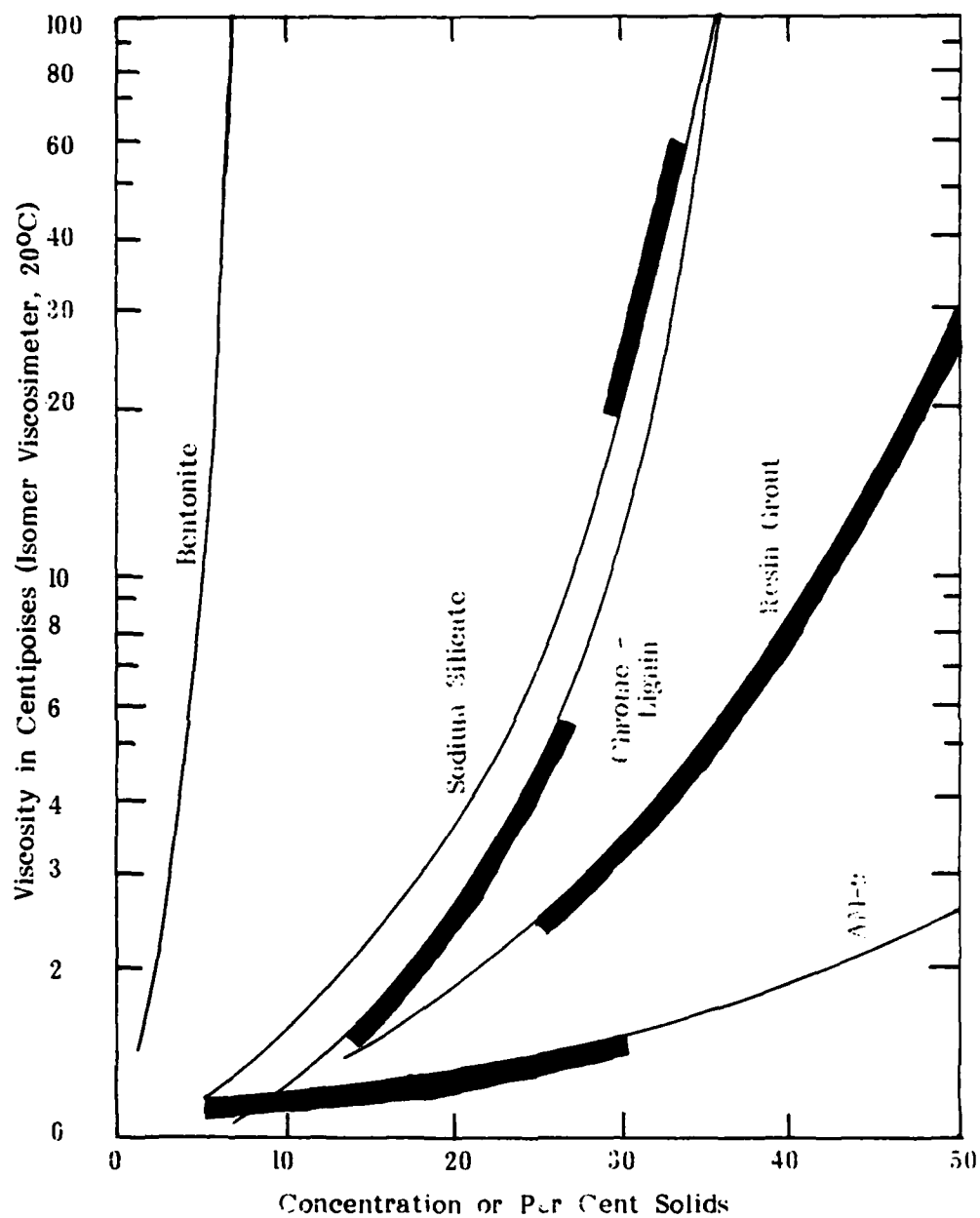
Figure 10. Viscosities of Various Grouting Materials as a Function of Grout Concentration (Herndon and Lenahan, 1976b) (The Solid Lines Represent the Concentrations Normally Used)

Grout setting time is very important in curtain wall construction. The use of grouts with short setting time for this purpose is advisable so that the flowing ground water does not take the grout out of the desired area.

c.   Permeability of Curtain Wall

The purpose of the curtain wall is to cutoff the flow of ground water from or to a particular area. Thus, in theory, the wall should be watertight, however, in practice complete watertightness is not practicably achievable. Instead, water permeability through the area is reduced to some acceptable rate, usually to a level where the coefficient of permeability is approximately 10^{-10} cm/sec. (Tollard and Caron, 1977b). To achieve this level of watertightness, the curtain wall must be uniformly constructed in the proper place. The ability to construct a uniform, watertight wall in the proper place is a function of the type of grout used, its viscosity, the type of injection process used and the ability to regulate the setting time. In addition to a uniform, properly placed wall, the overall watertightness also depends on the strength of the grout and its ability to withstand the hydrostatic pressure, and the long-term stability of the grout.

d.   Grout Strength

Curtain walls must remain in their intended position and not wash out under pore hydrostatic pressure. Resistance to pore hydrostatic pressure does not require the grout to have high mechanical stress. Thus, most mechanical tests performed on grout soils, e.g. unconfined compressive strength, have little bearing on the usefulness of the material for a curtain wall (Tallard and Caron, 1977b). Instead a penetration resistance test (Herrick and Brandstrom, 1966) or the vane shear test (Caron, 1965) have been recommended for testing of the strength of grouts for curtain walls (Tallard and Caron, 1977b).

e.   Grout Stability

The stability of the curtain wall is important if the ground water barrier is to be maintained over long periods of time. Most grouts, with the exception of the two shot silicates, are considered permanent. However, chemicals in the ground water can have a deleterious effect on the barrier material. Deterioration of the barrier can occur by reversal of the chemical reactions that created the solid material, dissolution of the wall materials, or through the removal of water from the grout matrix due to dessication, syneresis or condensation of the grout macromolecules (Tallard and Caron, 1977b).

In general, very little information is available on the long-term stability of the various grouts. Even less information is available on the long-term compatability of the grouts with various constituents of the ground water. There are no standard tests for durability of chemical grouts as there are for concrete and metals. Tallard and Caron (1977b) suggest grout curing procedures which would help standardize future stability tests.

f.   Toxicity

The toxicity of the grout material is important from two aspects: the individual toxicity of the grout materials to workers and the toxicity of the hardened grout and any unhardened materials to the ground water. Many grouts contain toxic components which react to form a non-toxic product. During grouting operations, the workers must be adiquately protected from exposure to any toxic components. However, more important in the selection of the grout is the possibility of contaminating the ground water with toxic materials. This contamination can occur during the actual grouting process if uncured material comes in contact with the ground water. The hardened grout can also present a toxicity problem when in contact with ground water. Some of the chemical reactions that formed the grout can be reversed to reform the starting materials by reaction with ground water constituents or unreacted reacted starting materials can be exuded from the grout by syneresis or seepage. Thus, the use of any toxic materials for grouting must be carefully evaluated if there is a possibility of contaminating the ground water. For a ground water cutoff barrier to contain a contaminated plume, the use of toxic materials for a grout curtain may not be a problem if the contained ground water is to be pumped and treated.

3.   Properties of Available Grouting Materials

A variety of particulate and chemical grouts with a wide range of properties are available from which to select a grout for a particular job. These grouts can be classified into the following categories:

Chemical Grouts

1.   Silicate Base

2.   Lignin Base

3.   Acrylamide Base

4.   Phenol Base

5.   Formaldehyde Base

6.   Isocyanate Base

Particulate Grouts

1.   Cement

2.   Bentonite

The properties of these grouts are summarized in Table VII and discussed below.

Table VIII. Properties of Currently Used Chemical Grouts (Partially abstracted from Herndon and Lenahan, 1976b)

Grout Material	Catalyst Material	Unconfined Compressive Strength of Grouted Soil, psi	Viscosity (Centipoise)	Setting Time Minutes	Toxicant*	Pollutant**
Silicate Base						
Low Concentration	Bicarbonate	10-50	1.5	0.1 - 3000	No	No
Low Concentration	Halliburton Co. Material	10-50	1.5	5 - 300	No	No
Low to High Concentration	SIROC-Diamond Shamrock Chemical Co.	10-500	4-40	5 - 300	No	No
Low to High Concentration	Chloride - Joosten Process	10-1000	30-50	0	No	No
Low to High Concentration	Ethyl Acetate Soletanche & Halliburton	10-500	4-40	5 - 300	No	No
Low to High Concentration	Rhone-Progis 600	-	-	-	No	No
Low to High Concentration	Geloc-3 H. Baker Co.	10-500	4-25	2 - 200	No	No
Low to High Concentration	Geloc-3x	10-250	4-25	0.5 - 120	No	No
Lignin Base						
Blox-All	Halliburton Co. Material	5-90	8-15	3 - 90	Yes	Yes
TOM	Cementation Co. Material	50-500	2-4	5 - 120	Yes	Yes
Terra-Firma	Intrusion Co. Material	10-50	2-5	40 - 300	Yes	Yes
Lignosol	Lignosol Co. Material	10-50	50	10 - 1000	Yes	Yes
Acrylamide Base						
AM-9	DMAPN and Ammonium or Sodium Persulfate	50-500	1.2-1.6	0.1 - 1000	Yes	Yes
Rocagil	Rhone Progil Material	-	-	-	Yes	Yes
Sumisoil	Sumitom Chemical Material	-	-	-	Yes	Yes
AC-400	Triethanolamine and AP	-	-	-	Yes	Yes
Aminoplasts						
Urea-Formaldehyde	Halliburton Co. Material	Over 1000	10	4 - 60	Yes	Yes
Urea-Formaldehyde	American Cynamid Co. Material	Over 500	13	1 - 60	Yes	Yes

Table VIII (cont.)

Table VIII. (cont.)

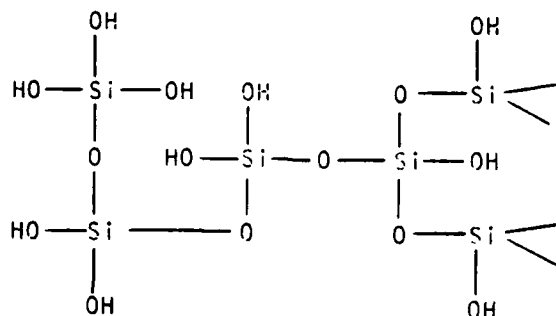| Unsaturated Fatty Acid Base						
Polythixon FRD	Cementation Co. Material	Over 500	10 - 80	25 - 360	No	No
Phenol Based						
Rogacil	Rhone Progil	-	5 - 10	-	Yes	Yes
Geoseal	Borden Co.	-	2 - 12	-	Yes	Yes
Terranean	ITT Rayonier, Inc.	-	-	-	Yes	Yes
Polyurethane						
TACSS	Takanaka, Komuten Co.	285-1700	24 - 400	variable	Yes	No
Epoxy						
Epseal	Halliburton Co. Material	-	80 - 90	-	Yes	Yes

- Information Not Available.

* Must be handled using safety precautions and/or protective clothing.

** Pollutant to fresh water supplies contacted.

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a. Silicate Based Grouts

The silicate grouts have been widely used throughout the world for waterproofing and strength improvement of soils. The basic ingredient of these grouts is sodium silicate with a silica/alkali ratio of 3 to 4. This material is formulated in an aqueous solution of various concentrations. The concentration of the sodium silicate in solution determines the viscosity of the grout and the unconfined compressive strength of the grouted soil. Grouts with higher concentrations of sodium silicate in solution have higher viscosities and result in grouted soils with a higher unconfined compressive strength. A setting reagent is added to the sodium silicate solution to promote gel formation. Gel formation occurs via a decrease in the electric charge on the silicate ions followed by polymerization of the silicate to form a reticulated tridimensional network having the following structure (Tallard and Caron, 1977a):

$$
\begin{array}{ccc}
\text{OH} & & \text{OH} \\
| & & | \\
\text{HO}-\text{Si}-\text{OH} \quad \text{OH} & \quad \text{O}-\text{Si}< \\
| \qquad\qquad | & \qquad | \\
\text{O} \quad\quad \text{HO}-\text{Si}-\text{O}-\text{Si}-\text{OH} \\
| \qquad\qquad | & \qquad | \\
\text{HO}-\text{Si}-\text{O} & \quad \text{O}-\text{Si}< \\
| & & | \\
\text{OH} & & \text{OH}
\end{array}
$$

The setting is promoted by a variety of reagents including acids, polyvalent cations and certain organics. The set time can be controlled by the amount of these reagents formulated into the grout.

There are two main methods used for grouting with silicate grouts – the Joosten (two-shot) method and the Siroc (one-shot) system. The two-shot method was originally conceived by Jeziorsky and applied by Joosten (Karol and Welsh, 1979). In this method, viscous solutions of the silicate grout and the setting reagent, usually calcium chloride, are injected separately into the ground either through the same pipe or through two adjacent pipes. When the two solutions meet, gel formation is instantaneous. The main disadvantages of this injection process are: 1) the higher costs associated with drilling the two adjacent holes, 2) the possibility that all the silicate grout will not come in contact with the reagent and thus will not set and 3) the high viscosity liquids cannot be pumped into soils of low permeability (less than 10^{-2} cm/sec) (Tallard and Caron, 1977a).

The two-shot process has been gradually replaced by the one-shot injection method. The one-shot method uses less viscous grouting solutions in which the silicate grout and the setting reagent are mixed. The set time is controlled by the amount of reagent added to the grouting solution. If formamide is used as the setting agent, the process is designated the Siroc System.

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The one-step method of silicate grouts injection is widely used for waterproofing. For this purpose, sodium silicate solutions of less than 30% are used. Sands having a permeability of 10^{-3} to 10^{-1} cm/sec can be waterproofed by this method. Reported permeability of the grouted soils are approximately 10^{-8} cm/sec (Karol and Welsh, 1979). If the permeability of the ground is above 10^{-2} cm/sec, then the formation should be initially grouted with a cemented based grout, otherwise, shrinkage due to loss of water (syneresis) will occur in silicate based grouts. Silicate grouts can also be leached in the presence of high water flows and thereby lose their waterproofing. The major advantages of silicate grouts are their low costs when compared to other chemical grouts and their non-hazardous and non-polluting properties.

b. Lignin Based Grouts

The lignin based grouts are made from a variety of lignosulfonates. These lignosulfonates are by-products of the wood-processing industry and vary significantly in composition. However, they are relatively inexpensive. The lignosulfonates form a gel upon oxidation/polymerizaton with hexavalent chromium in the presence of acid.

The lignosulfonate grouts can be formulated to different viscosities. Once mixed, the viscosity of the grout material changes with time so that it may become unpumpable before the set time. The set times can be controlled by varying the concentration of hexavalent chromium, acid, salt or water in the final formulation.

The lignosulfonate grouts can be used in sands having a permeability between 10^{-3} and 10^{-1} cm/sec. Reduction of soil permeability to 2×10^{-10} and 3×10^{-9} cm/sec with ammonium lignosulfonate and calcium lignosulfonate, respectively, have been reported (Weston and Kennerhey, 1958).

Lignosulfonate grouts have several disadvantages which have limited their use in the United States. These disadvantages include:

- loss of strength in a water saturated
  environment (Tallard and Caron, 1977a)

- tendency to leach chromium depending
  on the age of the grout, pH and pro-
  portions of chromium in the original
  formulation (Tallard and Caron, 1977a)

- toxicity of starting materials

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c.   Acrylamide Based Grouts

Acrylamide grouts were first marketed in the 1950's by American Cyanamid under the name AM-9. American Cyanamid no longer makes AM-9, however, other acrylamide type grouts are available:

Rocagil-from Rhone Progil Co., France

Sumisoil from Sumitomo Chemical Co., Ltd., Japan

A new acrylamide-like grout, called AC-400, has recently been introduced into the U.S. market by Geochemical Corporation.

The acrylamide grouts contain monomeric acrylamide which is polymerized by a redox-type catalyst in the presence of a reticulating agent such as N,N'-methylenebisacrylamide. The AM-9 product contained 90% of the acrylamide monomer and 10% of the N,N'-methylenebisacrylamide dimer. The redox catalyst used to catalyze the polymerization consists of an initiator such as ammonium persulfate (AP) or sodium persulfate and an accelerator such as diethylaminopropionitrile (DMAPN). The AC-400 grout uses an unspecified (but supposedly non-toxic) monomer, N,N'-methylenebisacrylamide dimer, ammonium persulfate initiator and triethanolamine accelerator (Geochemical Corp., 1980).

The viscosities of the acrylamide grouts are controlled by the amount of monomer in the formulation. Viscosities of 1 to 8 cP can be obtained by formulations ranging from 5 to 44% (Tallard and Caron, 1977a). These grouts have lower viscosities than any of the other grouts. Viscosity of the acrylamide grouts does not change with time after mixing, but remains constant until the set time. Thus, the pumpability of these grouts remains constant.

The set time for acrylamide grouts can be varied from less than a minute to several hours (Karol and Welsh, 1979). The set time is controlled by the monomer concentration and the proportions of the initiatior and activator used. If long set times are needed, a polymerization inhibitor, such as potassium ferricyanide, can be added to the formulation.

The permeability of acrylamide grout stabilized soils is approximately 10^{-10} cm/sec. This low permeability is due to the ability of the gel to absorb more water than present in its prepartion (Tallard and Caron, 1977a). Thus, these grouts are excellent for use in areas of 100% saturation but tend to shrink if dried. These grouts are not subject to syneresis (Karol and Welsh, 1979a).

The major disadvantages of acrylamide grouts are: 1) the high neurotoxicity of the acrylamide monomer and the toxicity of the accelerator and initiator, 2) high cost of these grouts, 3) the potential for hydrolysis in very alkaline media and 4) possible contamination of potable water supplies. The toxicity of the acrylamide monomer was a major factor in the discontinuation of this grout by American Cyanamid (Karol and Welsh, 1979). It has also been banned in Japan because of poisoning of well users from grouting operations (Karol and Welsh, 1979). The AC-400 grout has been formulated to eliminate these toxic problems but retain the low viscosity (approximately 2 cP) and low water permeability of the in   place grout.

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d. Phenoplast or Phenol Based Grouts

Phenoplast resins are condensation products of phenols and aldehydes formed under alkaline conditions. Three phenoplast grouts are on the market:

Rocagil - Rhone Progil in France

Geoseal - Borden in Great Britain

Terranier - ITT Rayonier, Inc. - U.S.A.

Rocagil is a solution of partially sulfonated polyphenols which react with formaldehyde in an alkaline medium to form a gel. The viscosity of this grout is 5 to 10 cP (Tallard and Caron, 1977a). Geoseal is a mixture of tanin and ammonia extracts which also react with formaldehyde in an alkaline medium. This grout has a viscosity of 2 to 12 cP (Tallard and Caron, 1977a). Terranier contains a polyphenol base (Tallard and Caron, 1977a).

The phenoplast grouts generally have low viscosities and can be used in soils of low permeability. The viscosity behavior of these grouts with time is similar to the acrylamide grouts in that the viscosity is relatively constant until the set time is reached. The set time is controlled strictly by the amount of water added to the grout.

The major disadvantages of phenoplastic grouts are their tendency to shrink and crack when dried and toxicity of grout constituents.

e. Formaldehyde Base Grouts or Aminoplasts

Urea-formaldehydes have found limited use as grouting materials. The main drawback to the use of these materials is the acid medium necessary for condensations. In soils, the acid catalyst needed to promote the condensation process is destroyed before it can affect the grout (Tallard and Caron, 1977a). Other drawbacks are the ammonia by-product formed during the condensation process and the toxicity of the grout constituents.

In spite of these drawbacks, urea formaldehyde grouts have been used successfuly in grouting operations. Both Halliburton Co (Herculox) and American Cyanamid (Cyanaloc) manufacture urea-formaldehyde grouts. These grout formulations use a prepolymer and have a viscosity of 10-13 cP. The set time can be easily controlled if prepolymers are used.

Because of the limited use of these grouts, there is essentially no information available on their durability or permeability.

f. Polyurethane Grouts

The polyurethane grouts are essentially a one liquid system containing an isocyanate which reacts with the ground water to produce a urea polymer. The reaction takes place as follows.

$$R\!\!<^{NCO}_{NCO} + 2 \cdot H_2O \longrightarrow R\!\!<^{NHCOOH}_{NHCOOH} \longrightarrow R\!\!<^{NH_2}_{NH_2} + CO_2\uparrow$$

$$n \cdot R\!\!<^{NH_2}_{NH_2} + 2n \cdot R\!\!<^{NCO}_{NCO} \longrightarrow \left[R\!\!<^{NHCONHRCO-}_{NHCONHRCO-}\right]_n$$
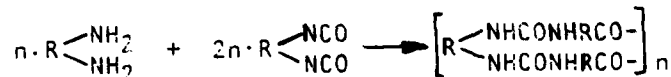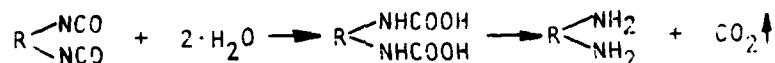
The carbon dioxide given off causes the grout to increase in volume and penetrate the soil. This type of grout is marketed by Takaneka Komuten Co., Ltd. of Japan under the name of TACSS (Takenaka Aqua-Reactive Chemical Soil Stabilization System). The viscosities of TACSS formulations are relatively high (greater than 20 cP) (Takaneka Komutan Co., Ltd., 1980). The set time of the grouts can be varied by addition of an amine to shorten the set time or an acid to prolong it. This grout is expensive and has not been used for grouting fine soils (Tallard and Caron, 1977a).

g. Epoxy Grouts

Epoxy grouts are non-water soluble organic resins. The resins are derived from the reaction of epichlorohydrin on 2,2'-bis(4-hydroxyphenol)propane (Bisphenol A). The resins can be polymerized or hardened by a variety of reagents including amino and carboxylic acids (Tallard and Caron, 1977a). The resin itself is very viscous having a viscosity of greater than 400 cP. This viscosity can be lowered to approximately 20 cP by careful choice of the hardener and dilution with organic solvents (Tallard and Caron, 1977a). The mechanical strength, watertightness and durability of the epoxy grouts are excellent, however, their high costs, difficulty in regulating set time and toxicity of components have resulted in limited use of grouts.

h. Bentonite Grouts

Bentonite grouts differ from the chemical grouts in that they contain particles. These particles are usually less than one micron in size if a peptizer has been added to prevent flocculation. These grouts exhibit thixotropic behavior. When at rest, they are rigid with a high apparent viscosity. When subjected to shearing forces, the viscosity of the bentonite decreases and it behaves as a fluid. For grouting purposes, the bentonite is formulated to a viscosity of approximately 15 cP. A peptizing agent is usually used to maintain the ultra-colloidal properties of the material. During the grouting process, the bentonite slurry will gradually become more viscous as it moves out from the bore hole into the ground. If the injection pressure is increased, the bentonite will again become fluid.

Bentonite grout has very low strength characteristics and thus cannot be used for soil consolidation. Bentonite has good waterproofing characteristics which makes it a good ground water cutoff barrier. A second advantage of bentonite is its intrinsic rigidity which prevents the grout from traveling downward in the soil. The major drawback to bentonite is its lack of mechanical strength which allows the grouted areas to loosen and lose their watertightness.

Combinations of bentonite with chemical grouts have been used to advantage. One such combination is Supergel which consists of bentonite, a peptizer, sodium silicate and a setting agent which does not flocculate the bentonite. Supergel has the intrinsic rigidity of bentonite, thus preventing downward drifting, optimal rheological properties with a viscosity of approximately 3 cP, less tendency for syneresis than the silicate, better mechanical characteristics than bentonite and is non-polluting and non-toxic (Tallard and Caron, 1977a).

i.   Cement Grouts

Cements have been used in the construction industry since the 1800's for grouting purposes. In the U.S., Portland cement has been the chief grouting material. This cement has been extensively used for increasing the load bearing characteristics of the soil. It has also been used for water cutoff. For this purpose, it is usually formulated with other materials such as bentonite and/or sodium silicate. These formulations are less expensive than cement itself, exhibit better permeability properties and are more resistant to attack by chemicals.

4.   Injection of the Grout

a.   Grouting Patterns

Once the grout for the job has been selected, placement of the injection holes and their depth must be determined. For construction of a grout curtain, the injection holes are arranged in a grid pattern of sufficient length to cover the area. The injection holes should be arranged in at least two or preferably three staggered rows as shown in Figure 8a. The distance between the holes should be less than two times the grouting radius, r, to insure a continuous curtain (Herndon and Lenahan, 1976b). The grouting radius can be determined once the grout material is selected and the porosity of the soil is known by the following equation:

$$r = 0.62 \sqrt[3]{\frac{Qt}{n}}$$

where

r = radial distance of grout penetration, cm

Q = rate of grout uptake by the soil, cm^3/min

n = porosity of the soil

t = pumping time, minutes

Once the pipe spacing and pattern, and the porosity of the soil have been determined, the amount of grout needed can be determined by referring to Figure 11 (Herndon and Lenahan, 1976b). The time required to pump the grout can then be calculated:

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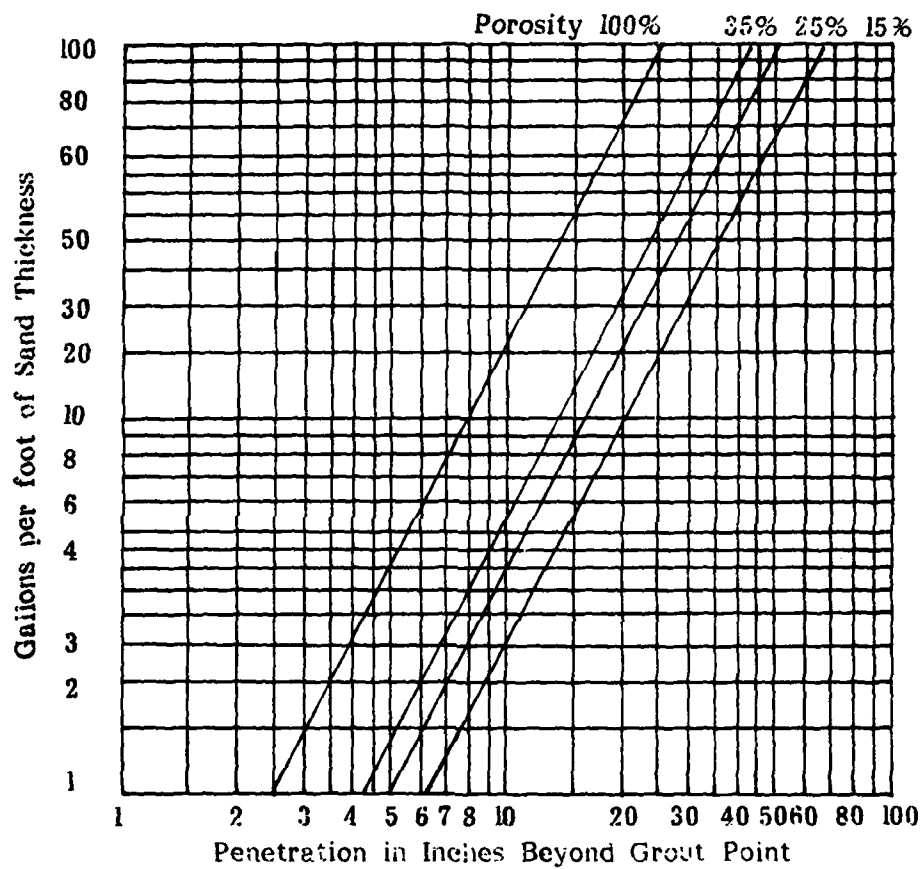
Figure 11. Grout Volume Required to Radially Fill Soil Around Grout Pipe (Herndon and Lenahan, 1976b)

$$t = \frac{V}{Q}$$

where

> V = grout volume in gallons from Figure 11
>
> Q = grout flow rate, gal/min which can be
>   calculated from Darcy's radial flow equation

$$Q = \frac{(0.316) \ k \ h_t \ (Pw\text{-}Pc)}{N \ \ln r/r_o}$$

where

> k = permeability, darcy
>
> h_t = thickness of soil grouted, cm
>
> Pw = well bore pressure, atm
>
> Pc = boundary pressure, atm (usually zero)
>
> N = grout viscosity, cP
>
> r = radius of grouting, ft.
>
> r_o = radius of injection pipe, ft.

b.   Grouting Equipment

The equipment used in grouting operations consists of a mixing and pumping system and the injection pipe. Three types of mixing systems have been used for grouting operations: 1) batch system, 2) two stream equal volume pumps and 3) two stream variable pumps. The batch mixing method is the simplest and the most popular system. All the ingredients of the grout are mixed together in one tank. The mixed material is pumped into the ground through the injection pipes. Positive displacement or progressive cavity pumps are normally used to pump the grout. The prime disadvantages of the batch mixing system are (Herndon and Lenahan, 1976b):

- the entire batch must be injected before the
  grout becomes too viscous to pump

- set times cannot be changed once the mix
  is formulated

- short set times cannot be used.

In the two stream mixing systems, the grout components are pumped, by either equal volume or proportional pumps, into a mixing head. The components are mixed in the mixing head as they are injected into the ground. This type of system can be used with short set-time grouts. The grout set time can be changed during the operation if proportional pumps are used.

There are several types of injection pipes available. These pipes, their advantages and limitations are described in Table VIII. The type of pipe used is usually a function of the contractor selected for the job, as an individual contractor will normally use the same pipe for all grouting jobs.

The actual grouting operation is performed by grouting every other hole in row A (Figure 8a). Then every other hole in row C is grouted. The remaining holes in rows A and C are grouted followed by all the holes in row B in order (Herndon and Lenahan, 1976b) To prevent fracturing or uplifting of the soil, grouting injection pressures should be less than 1 psi per foot of overburden depth (Herndon and Lenahan, 1976b).

c.   Quality Control

Since the grout spread is underground, the integrity of the wall cannot be known with absolute certainty until pollutant penetration is monitored for some period of time or an excavation test is performed. Therefore, accurate records should be maintained of the mixing procedures, injection pressures, flow rates and total grout injected at each hole. If a leak in the curtain should develop, these records will help to identify the possible location of the leak.

Research is currently underway to determine if geophysical sensing methods such as A C electrical resistivity, acoustic velocity and earth probing radar can be used to determine the location and condition of injected grout (Hayward Baker Co., 1980).

d.   Imper-wall Technique or Vibrated Membrane

This technique is an off-shoot of the slurry-trench and grouting processes. It involves inserting a thin screen or layer of grout into the ground by first making a continuous slot in the ground with steel sheet H piles. As the piles are removed from the ground, the grout is injected under pressure into the slot. Basically a reinforced H pile with grout pipes welded to it is injected into the ground with a diesel vibratory hammer. The pilings are driven into the ground adjacent to one another as shown in Figure 12. As the pilings are removed, the grout is injected into the slot under pressure, filling the slot. (Xanthakos, 1979; Schmednecht, 1976).

The Imper-wall technique works well in saturated loose granular soils and thin layers of clay and silt. Medium and stiff clays have to be pretrenched (Schmednecht, 1976). Depending on the grout used, good reduction of permeability across the area can be obtained. Added advantages of the Imper-wall technique include compaction and densification of the soil mass leading to lower permeability and smaller volume requirements for expensive grouts. The major disadvantages of this type of grouting are the length of time required for the grouting operations, high cost of equipment and frequent equipment breakdowns (Schmednecht, 1976). According to Schmednecht (1976), over 50 million square feet of this type of wall have been installed in Europe with no failures and 1 million square feet in the United States.

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Table VIII. Types of Injection Pipes for Grouting From the Surface (Herndon and Lenahan, 1976b)

	Name	Description	Placement	Advantages	Limitations
A.	Drive Rod (Lances)	EW Rod with special pointed end or extrudable plug.	Driven in ground	Pipe retrieved. Can grout in zones or stages.	For depths to about 50 ft. Requires driving equipment
B.	Slotted Pipe	Plastic pipe with slots.	Set in borehole w/gravel and grout.	No special equipment required	Can grout only one zone.
C.	Tube a Manchette	Plastic pipe with sleeve covered holes at given intervals (French origin, available in Europe).	Set in borehole with weak grout. Uses inner pipe with packers to straddle holes.	Can grout selectively and regrout as desired.	May not be available in th United States.
D.	Lost injection element	Single section element with sleeve covered holes (Netherlands).	By special steel tube with small plastic hose to surface. Element is left in ground.	Simple if contractor has equipment required.	May not be available in th U.S. Special placement vit rator crane is required. Ca only grout one section abo 1 meter thick.
E.	Open Hole With Packer	Uses cased hole with air packer set in end of casing above zone to be grouted.	In borehole.	Can stage grout as desired.	Requires pucker and air source.
F.	Stabilator Valve Tube	Steel drilling system also used for grouting (Swedish).	Drills with pipe, then knocks off bit and uses pipe for grouting.	Can grout selectively.	May be hard to obtain in the United States.

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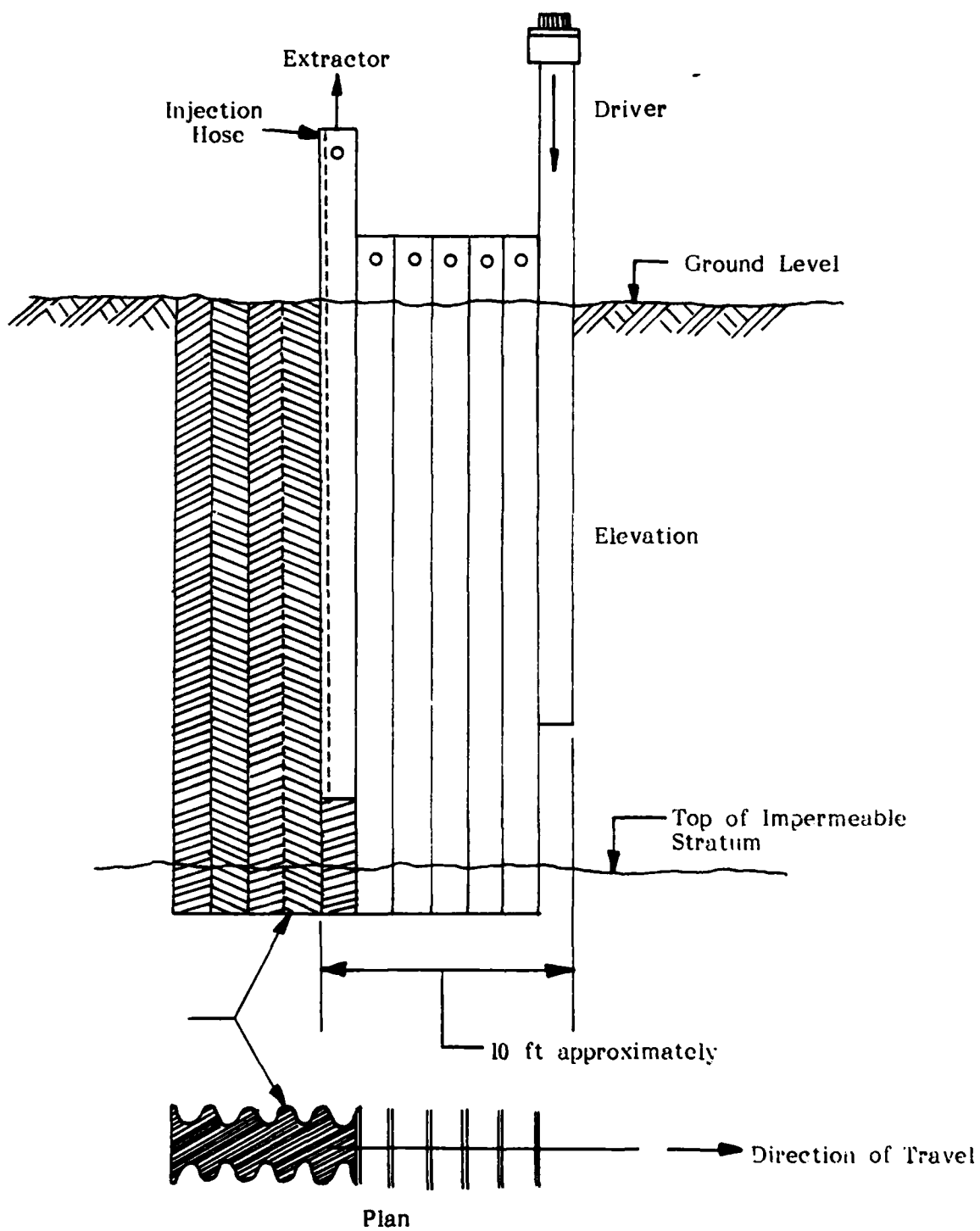Figure 12. Method for Installation of Imper-wall (Xanthakos, 1979)

C.   Performance

        Grout curtain walls can reduce the permeability across a selected area from 10^{-2} cm/sec to 10^{-8} to 10^{-10} cm/sec. The effectiveness of this technique for water cutoff is dependent on the following factors:

-     careful pretesting to determine soil and ground water
       characteristics

-     selection of the proper grouting material for the soil
       physical characteristics and the chemical characteristics
       and flow of the ground water

-     careful planning of the actual job with adequate
       quality control

        Grouting has been used for years by the construction industry for soil consolidation and water proofing. Some examples of grouting jobs for waterproofing are listed in Table IX. In some of these jobs, grouting was used to repair existing leaky dams or ponds. In other jobs, the total water flow was cut off by grouting procedures.

D.   Economics

        Costs for installing grout curtains of several types are listed in Table X. The cutoff wall is 1067 m long and 8.2 m deep. Soil porosity is assumed to be 33%. Grout pipes are placed every 1.5 m with 0.8 m between rows. Thin wall cutoffs are assumed to be 9 cm thick. Costs were obtained from manufacturers and contractors, and there was wide variation in the estimates given. In view of discrepancies such as the vast cost difference seen for two estimates of cement grouting, it is very difficult to draw valid conclusions from the information in this table. A 1975 estimate (Atwell, 1975) sets grouting costs at $161.5/m^2$. Scaling to 1980 costs with CE cost index, costs for the wall are $2,045,400. This falls between the two and three row estimates from Martin Marietta (1980) and Herndon and Lenahan, (1976b), so these numbers are considered more reliable than the low estimate given by W.G. Jaques, Inc.

Table IX. Grouting Applications for Waterproofing

Location	Type of Material	Application	Degree of Success	References
Mine 14-042A Clarksburgh, W. VA	Halliburton PWG grout fluid	Slurry pumped into an expendable grout container to close mine	Demonstrated feasibility, some leakage after 4 years, costs higher than conventional techniques	Halliburton, 1967
-	Acrylamide flyash grout	Seal mine	Not successful due to high ground water flow	Chung, 1973
Mine 62-008 Clarksburg, W. VA	Slurry 1 - cement Slurry 2 - bentonite and sodium silicate	Slurry mixed together as pumped into mine between 2 bulkheads	Successful, no seepage after 2 1/2 years	Scott and Hays, 1975
E.I. DuPont LaPorte, TX	Chemical grout	Control seepage through dike of sludge lagoon	-	Raymond International Builder, Inc., 1979
E.I. DuPont Edgemoor, DE	Chemical grout	Control leakage through and under sulfate mud ponds	-	Raymond International Builder, Inc., 1979
Allied Chemical Corp. Baton Rouge, LA	Chemical/cement grout	Control leakage through HF residue pond dike	-	Raymond International Builder, Inc., 1979
Allied Chemical Corp Nitro, W. VA	Chemical and cement grout	Control dike leakage from residue ponds	-	Raymond International Builder, Inc., 1979

Table IX. (cont).

FMC Corp., ICD Grand River, WY	Chemical and cement grout	Control seepage through and under dikes from ash settling pond	-	Raymond International Builder, Inc. 1979
Chevron Oil Co. Perth Amboy, NJ	Silicate based grout	Cutoff wall to wharf area to prevent the migration of petroleum products into river	-	Raymond International Builder, Inc., 1979
American Smelting and Refinery	?	Control seepage through tailings dam	-	Raymond International Builder, Inc. 1979
Harmon Colors Co. Haledon, NJ	?	Control seepage through dikes of raw water cooling pond	-	Raymond International Builder, Inc. 1979
Philadelphia	Terranier-C	Control petrochemicals from seeping into an interceptor sewer	Successful	Raymond International Builder, Inc. 1979
-	Clay, cement and bentonite	Control seepage of ^{226}Ra from tailings pond into nearby recreational waters	Curtain wall did not cutoff all ground water flow but did stop migration of ^{226}Ra by either a longer path and increased filtering action or chemical reaction with the wall clay	Dodds et al. 1978
Research	Silicate-based	Control spread of a hazardous chemical spill	-	Huibregtse et al., 1978

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Table IX. (cont.)

Ortho Chemical Thin Wall Cutoff	Aspermix Emulsified Asphalt	Control seepage into pesticide containing lagoon	Successful (Tested at 10^{-11} cm/sec)	Harmston, 1980
Romulus, MI Thin Wall Cutoff	Aspermix Emulsified Asphalt	Isolation of pond containing phenols, benzene	Successful	Harmston, 1980
Thin Wall Cutoff	Bentonite-Flyash Mixture	Isolation of chemical waste with high sulfate content	Worked as well as cement-bentonite	Harmston, 1980

- not available

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Table X. Economic Analysis for Various Grout Curtains and Imper-wall for Rocky Mountain Arsenal

Type of Grout	Material Costs	Construction	Mobilization	Materials and Construction	Cost for Cutoff Wall Described below
Cement 2 rows	$3.34/94 lb sack[1] 1.44 sacks/ft depth[2]	$1200/day, 1 hole/day	$700-800[5]	$4/ft^{2}	$378,000-$1,862,600
Cement 3 rows	$3.34/94 lb sack[1] 1.44 sacks/ft depth[2]	$1200/day, 1 hole/day	$700-800[5]	-	$2,793,500
Isocyanate 2 rows	$1100/50 gal, swells 6-8 times original volume	$1200/day, 1 hole/day	$700-800[5]	-	$7,512,400
Isocyanate (20% of voids) - cement (30% of voids) 2 rows	$1.84/ft^{3} stabilized	$1200/day, 1 hole/day	$700-800[5]	-	$2,984,900
Acrylamide 2 rows	$33.67/ft depth [1, 2]	$1200/day, 1 hole/day	$700-800[5]	-	$2,953,500
Cement thin wall cutoff	-	-	$18,000-$30,000[6]	$3/ft^{2}	$301,500-$419,600
Aspermix (emulsified asphalt) thin wall cutoff	-	-	$18,000-$30,000	$4.25/ft^{2}	$419,600-$431,600
Silicate (15%) 2 rows	$6.25/ft depth	$1200/day, 1 hole/day	$700-800[5]	-	$2,953,500

1 Martin Marietta Corp., 1980

2 Herndon and Lenahan, 1976

3 TJK Price List, April, 1980

4 Fleming letter, 1980

5 Fleming conversation, 1980

6 Harmston, 1980

7 Tomstock, 1980

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E.   Advantages and Disadvantages of Grout Curtain Cutoff Walls

Grouting is a well established procedure in the construction industry for waterproofing and stabilization of soils. Thus, many companies have the equipment and technical know-how to perform satisfactory grouting jobs. U.S. companies with experience in the grouting field are listed in Table XI (not inclusive). A variety of grouting formulations are on the market so that a material or combination of materials to meet the requirements of any job should be readily available. Grouting can lower the permeability of an area to less than 10^{-8} cm/sec if the proper grout and injection techniques are used.

There are several disadvantages of grouting for water cutoff. Grouting cannot be accomplished in soils having permeabilities less than 10^{-5} cm/sec. The cost of grouting soils with permeabilities of greater than 10^{-3} cm/sec is significantly higher than for soils of permeabilities of 10^{-1} to 10^{-3} cm/sec due to the higher cost of the grout materials. The maximum depth of grout curtains is approximately 60-80 ft. At greater depths, the cost increases due to the need for specialized drilling equipment. Grouting materials are generally more costly than those for slurry-trench work. The equipment required is also more sophisticated and the labor costs are higher. Another disadvantage of grouting, is the extensive amount of planning and pretesting required to insure selection of the proper grout material and grouting techniques. This process can be further complicated by the proprietary nature of some grout materials and their injection techniques, thus, comparisons of cost/performance data are difficult. Another significant disadvantage of this technique is the lack of monitoring procedures to determine the placement and condition of the grout in the soil. To date, the only methods to determine if a satisfactory grout curtain has been installed are by monitoring of test wells or test excavation of the site.

The use of the Imper-wall installation technique can overcome some of the problems and costs associated with planning of the grout curtain for conventional grouting. It also has a lower cost than conventional grouting techniques, however, less is known about its permeability and durability.

Table XI. U.S. Companies with Expertise in Grouting

Hayward Baker Co.
1875 Mayfield Road
Odenton, MD 21113
(301) 621-9400

Chemgrout Inc.
805 East 31st Street
La Grange Park, IL 60525
(314) 354-7112

Dean Jones Contractor
410 Opal Street
Clinton, OK 73601
(405) 323-0798

Eastern Gunite Co.
240 Rock Hall Road
Bala Cynwyd, PA 19004
(212) 664-5590

Foundation Sciences, Inc.
Cascade Building
Portland, OR 97200
(503) 224-4435

Geologic Associates, Inc.
Reynolds Road
Franklin, TN 37064
(615) 794-3596

Geron Restoration Co.
7 Wells Street
Saratoga, NY 12866
(518) 587-0437

Halliburton Services
P.O. Drawer 1431
Duncan, OK 73533
(405) 251-3760

Hunt Process Co., Inc.
P.O. Box 2111
Santa Fe Springs, CA 90670
(213) 941-0231

Intrusion Prepakt Co.
1705-T The Superior Building
Cleveland, OH 44114
(216) 623-0080

Northern Systems, Inc.
20702 Aurora Road
Cleveland, OH 44146
(216) 475-2072

Penetryn Systems, Inc.
424 Old Niskayuna Road
Lathan, NY 12110
(518) 783-2958

Pressure Grout Co.
S Lyndon Street
Los Angeles, CA 94015
(415) 871-2244

Raymond International, Inc.
Soiltech Department
6825 Westfield Avenue
Pennsauken, NJ 08110
(609) 667-3323

SOLINC
Soletanche and Rodio, Inc.
6849 Old Dominion Drive
McLean, VA 22101
(703) 821-6727

V. SHEET PILING CUTOFF WALL

A. Introduction

Sheet piling cutoff walls work on the same principle as slurry walls and grout curtains: an impermeable barrier is placed underground to divert ground water flow around a particular area. Sheet piles are typically used for bracing in trenches and excavation, retaining walls, and bulkheads. They are used to keep earth in place or to keep water out of an area (Pulver, 1960). To date, sheet pilings have not been used to prevent ground water flow through a contaminated region (Beck, 1980), however, in principle, the method should work.

B. General Description

A sheet of piling cutoff wall is constructed of a series of metal plates driven into the ground and interconnected at their edges. Several common types of sheet piles are shown in Figure 13. Z piles are strongest and can withstand the largest horizontal forces. Straight piles are the weakest, with pan or hat types falling somewhere in between (Coastal Pile Driving, 1980). Piles may be driven by hand (up to approximately 4.6m) by drop hammer, by power hammer, or by jetting (Pulver, 1960). Sides of the piles are interlocked by ball and socket joints along their edges. Sections are assembled above ground, driven in stepwise so that each pile can provide support against bending to the pile beside it. Pile sections have been driven to depths of 30.5 m (Tolman et al., 1978), but depths up to 15.2 m are more common (Pulver, 1960).

C. Performance

Sheet piling is normally fabricated from hot rolled carbon steel (U.S. Steel, 1968). Carbon steel corrodes very rapidly in dilute acid. Brine or sea water will corrode the material more slowly, while organic chemicals and neutral water appear to have little effect (Norden, 1973). With carbon steel piling, there is also some danger of iron contamination of the surrounding ground water (Norden, 1973). There are some marine piles available which are more resistant to sea water. For large jobs, U.S. Steel or Bethlehem is generally willing to undertake a study and recommend appropriate additives for a particular application (Coastal Pile Driving, 1980). In construction applications, sheet piling cutoff walls have far exceeded their anticipated lifetimes. Under a wide variety of soil conditions, pilings ranging in age from seven years to forty years, were found to be the be relatively free of corrosion. The damage that was observed was not sufficient to affect the material's strength or useful life (Tolman et al., 1978).

While a sheet piling cutoff wall is never completely watertight, it can substantially reduce the flow of ground water. In cofferdam construction, for example, a small pump used in conjunction with steel sheet piling is sufficient to keep the isolated area dry (Coastal Pile Driving, 1980). Performance in silty or fine soils is improved after installation by the entrapment of soil particles in small gaps in the interlocking edges (Tolman et al., 1978). As with slurry walls and grout curtains, sheet piling cutoff walls can extend partway or all the way to an impervious layer.

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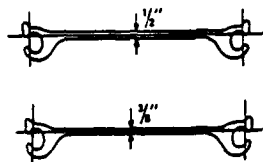
STRAIGHT PILES
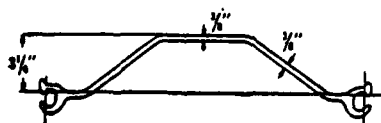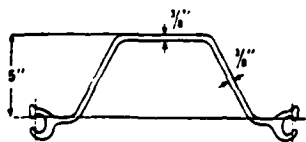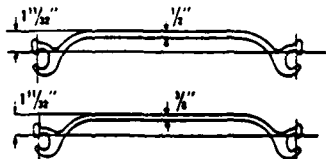
PAN OR HAT PILES
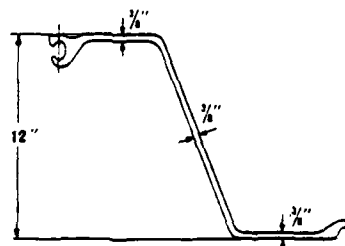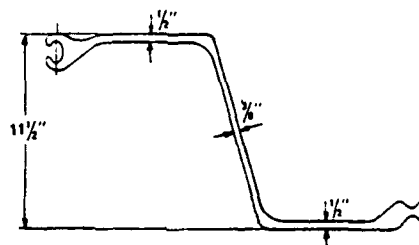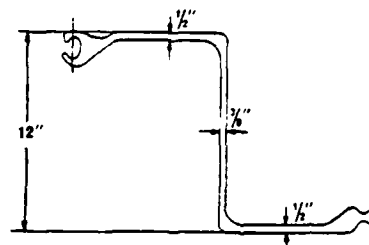
Z PILES

Figure 13.   Sheet Piling Section Profiles (U.S. Steel, 1968)

D.   Costs

An analysis developed by Tolman *et al.* (1978) predicted the cost for a 518 m long, 18 m deep sheet piling cutoff wall would fall between $650,500 and $956,500. In 1980 dollars, the cost per square meter is $82.56 to $139.94. An estimate by Coastal Pile Driving puts the cost currently at around $139.94/m^2. Material costs account for roughly 50% of the total installed cost. For comparison with other methods, a 1067 m x 8.2 m wall at Rocky Mountain Arsenal could be expected to cost between $725,000 and $1,230,000.

E.   Advantages and Disadvantages of Sheet Piling Cutoff Walls

Sheet piling cutoff walls have several advantages which may make this option attractive. Construction is straightforward, requires no excavations, and can be performed with readily available materials by contractors throughout the U.S. (Tolman *et al.*, 1978). As with slurry walls and grout curtains, sheet piling cutoff walls require no maintenance after installation. Protective coatings or sacrificial anodes can be applied to the finished piling to help resist corrosion (Tolman *et al.*, 1978).

There are also a number of disadvantages with this method which will probably discourage its use for pollution control. Most importantly, the technique as never been tested in this application. The threat of corrosion is always present, particularly if there is some deviation in soil conditions from those for which the wall was designed. Finally, the costs may be higher than those for other methods which perform as well or better.

VI. SYNTHETIC MEMBRANE CUTOFF WALLS

A.   Background and Construction

Synthetic membranes can also be used to form a cutoff wall to divert or contain ground water. Synthetic membranes which have been used for lagoon and landfill liners, e.g. hypalon and polyethylene, could be used for this purpose. Significant testing has been performed to determine the compatibility of these liners with chemical wastes. Therefore, the durability of the liner exposed to chemicals is not as great an unknown as with grouts or sheet pilings.

The placement of a synthetic membrane liner into the ground for a vertical ground water barrier is relatively straightforward as shown in Figure 14. A trench is dug from the surface to an impervious soil layer. A drain is laid in the bottom of the trench to carry away excess water to a pumping well or surface collection point. The synthetic membrane is suspended vertically in the trench and the trench is backfilled with sand or other suitable material. Thus, the major construction equipment needed consists of a trench digger, e.g. backhoe, a bulldozer for filling the trench, and pipe laying equipment.

B.   Advantages and Disadvantages of Synthetic Membrane Cutoff Walls

Synthetic membranes should make good ground water cutoff barriers if properly installed. The materials are available in a wide variety of compositions with relatively well known chemical compatabilities. The membranes are flexible enough to accomodate earth movement or settling.

This type of cutoff wall can have several disadvantages depending on the type of membrane chosen and the site. First, construction of the trench may be difficult if the soil is non-cohesive or a high rate of water infiltration is present due to cave-in of the trench walls. In these cases, bentonite slurry or other stabilizers will probably have to be used to stabilize the trench. A second disadvantage is the uplifting of a corner of the membrane by the ground water flow or in the backfill process thus allowing water to flow around the barrier. Coarse gravel or rocks in the backfill can also tear the liner.

Several methods for overcoming these difficulties have been forthcoming. The first method is to install the membrane in a slurry-trench. This technique has the advantage of trench side support and stopping water infiltration in the digging process. The presence of a membrane results in a slurry-trench with less permeability and more resistance to chemicals in the ground water. Synthetic membranes have been installed in slurry-trenches in the U.S. (Henry, 1980), however, specific site information is unavailable.
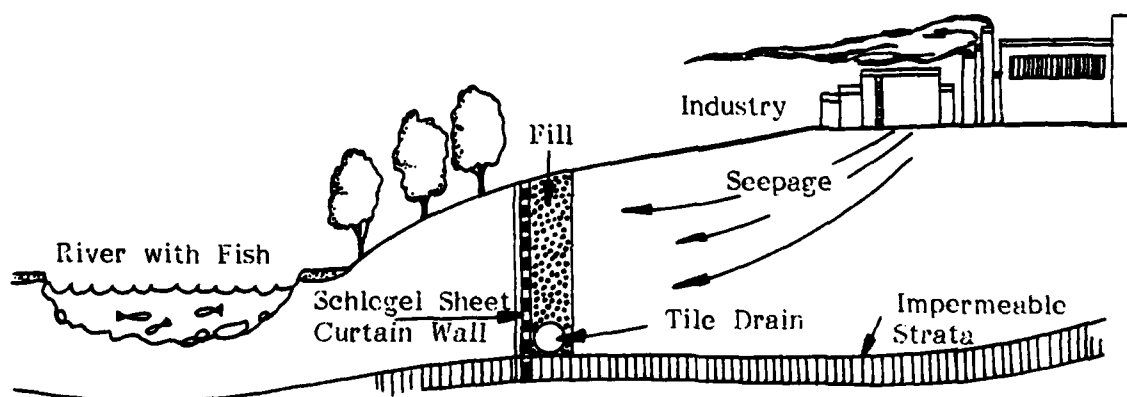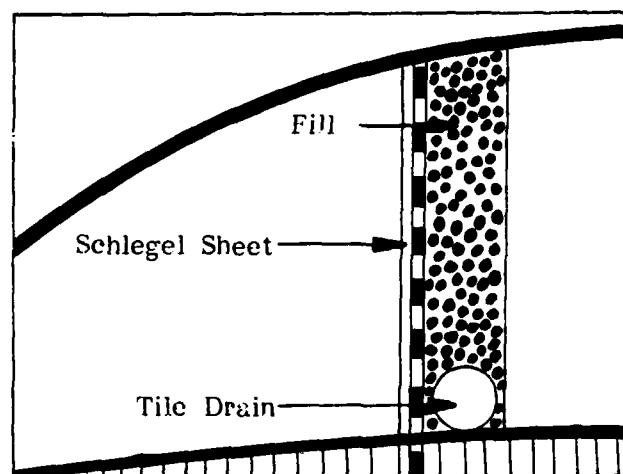
Figure 14. Synthetic Membrane Vertical Ground Water Barrier
(Schlegel Engineering, 1977)

Schlegel has developed a thick (3.5 mm), high density polyethylene liner material which has been successfully used for vertical ground water cutoff applications in the Middle East. This membrane has not been used for this purpose in the United States (Clark, 1980). This membrane is flexible enough to move with ground shifts but will not lift up from ground water flow or during backfill. Gravel or rocks in the backfill operations will not pierce the membrane.

C.   Costs

The costs of placing a synthetic membrane in the ground for a vertical ground water cutoff barrier are difficult to assess. If placed in slurry-trench, the cost will be that of the slurry-trench plus the cost of the liner and the labor for installation. For the 1067 m x 8.2 m, Rocky Mountain Arsenal barrier, the cost would be:

cost of slurry-trench	$662,000
cost of liner (8000 m^2)	13,993
TOTAL	$675,993

Complete installation of Schlegel's high density polyethylene liner costs from $8.61/m^2 to $129.17/m^2 depending on site, liner, weather, etc. (Clark, 1980). Cost estimates for installation of this liner at Rocky Mountain Arsenal range from $75,332 to $1,130,160. The costs include pump and drain installation, but not the cost for pump electricity and trench maintenance. These yearly costs are estimated in the next section on French drains.

VII. FRENCH DRAIN OR INFILTRATION GALLERIES

A. Background and Construction

A French drain or infiltration gallery consists of a horizontal trench containing perforated pipe lying near the trench bottom. The pipe is embedded in crushed stone or gravel. The remainder of the trench is filed with a permeable material such as sand. The trench may or may not have a liner on the downgradient side to prevent any seepage past the drain. This configuration would be similar to that described under synthetic membrane barriers. Water seeps into the drain from the upgradient side, enters the pipe and is pumped to the surface through a vertical riser pipe for treatment.

Construction of a French drain can be accomplished with a backhoe. The cost of the trenching varies with depth, type of soil and ground water levels. Usually costs increase at depth greater than 7.6 m, in cohesionless soils and in the presence of high ground water due to problems in stabilizing the sides of the trench. French drains have been widely used in agricultural and construction to drain swamp lands, thus their construction techniques are well established.

As with other ground water barriers, a site survey is required to determine the type of subsurface soil and the characteristics of the ground water. Once the presite survey is completed and the location of the drain is determined, any qualified construction company can be engaged to construct the trench. Albert Elia Construction Co. of Niagara Falls, New York is building the French drains at the Love Canal. Schlegel has considerable experience in installation of French drains with downgradient membranes, mainly in Europe.

B. Performance

French drains or infiltration galleries can be used to collect ground water to divert it away from a landfill or lagoon or to collect contaminated ground water for treatment. Tolman et al. (1978) proposed the use of French drains for collecting contaminated leachates from landfills or to divert upgradient ground water. The use of French drains to recover oil spills from ground water was proposed by Dennis (1977). A French drain was also considered for Rocky Mountain Arsenal (Thomas et al., 1977).

The first major use of French drains to collect underground leachate instead of ground water runoff is at the Love Canal (Glaubinger et al., 1979). This drain system, shown in Figure 15, collects the leachate from the dump site after which it is passed through activated carbon to remove the organics (Glaubinger et al., 1979). These drains are 3.7 - 4.8 m deep and contain perforated, 20 cm vitrified clay pipe embedded in 0.7 m of gravel and topped with sand. There are no downgradient liners. The ability of this system to completely stop all leachate migration still remains to be determined.
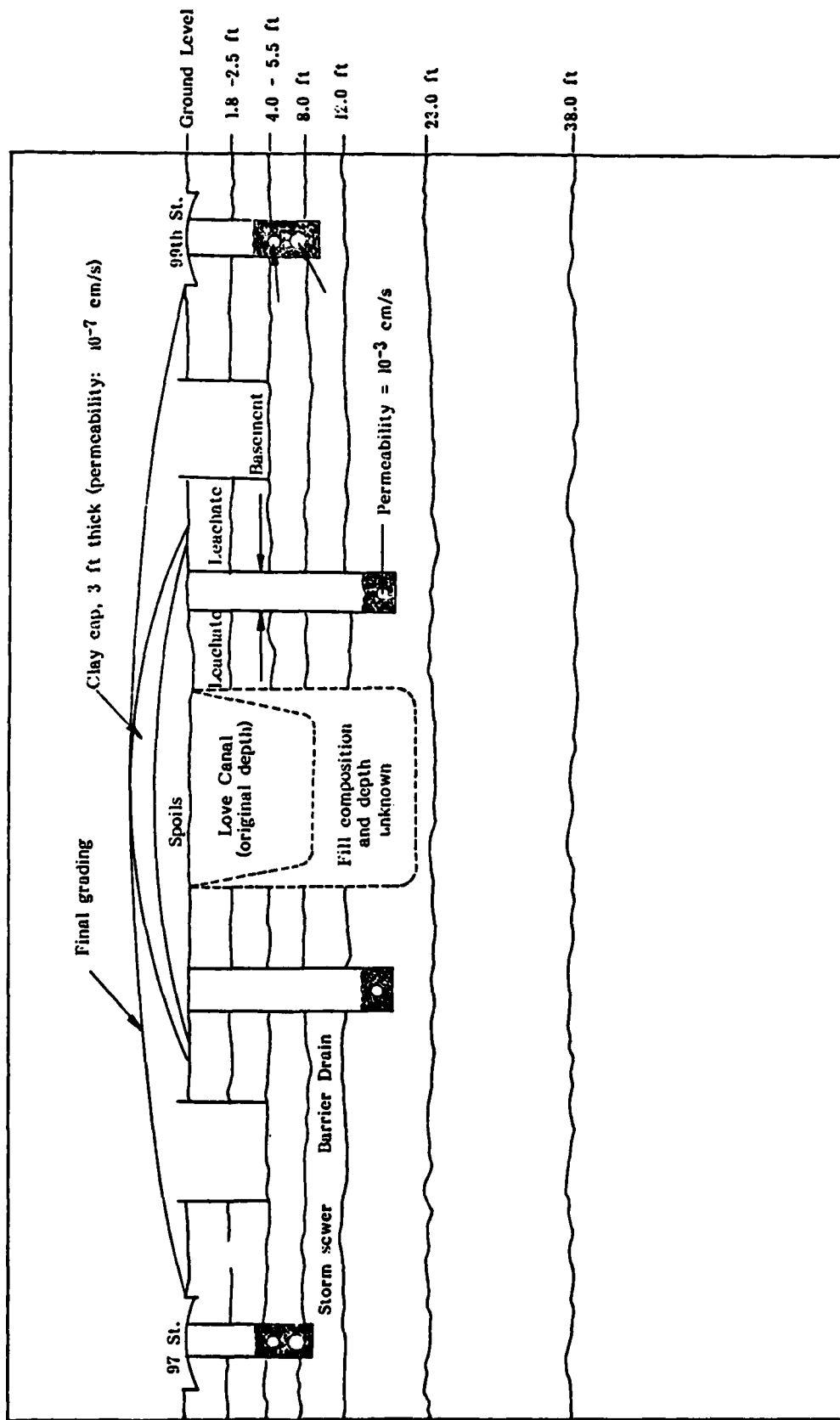
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Figure 15. Underground Leachate Collection Drains at the Love
Canal (Glaubinger et al., 1979)

C.   Costs

The costs for construction of a French drain at Rocky Mountain Arsenal are presented in Table XII. This drain would be 1067 m long, 8.2 m deep and 0.91 m wide. Total installation costs are $304,735 for an unlined drain and $318,728 for a lined drain. The first year's operating costs for cleaning the drains and operating the pumps are estimated as follows:

Labor/yr	$ 4,370
Materials/yr	2,400
Power/yr (two 21 hp pumps each operating 85% of the time)	14,000
TOTAL/yr	$20,770

With a yearly escalation of 12%, total operating costs for ten years would be $363,475. Thus, the total capital and operating cost of the French drain system would be $668,210 - $682,203.

If special trenching (anything needing equipment other than a backhoe) is required, construction costs could increase significantly. Thomas et al. (1977) used a cost of $656/linear meter (1977 basis) for the trenching operation for a French drain at Rocky Mountain Arsenal. This cost would translate into $846/linear meter in 1980 dollars. Using this figure, the trenching costs alone for the 1067 m boundary would be $902,682. This number appears to be excessive even for special trenching operations.

D.   Advantages and Disadvantages of French Drains

French drains can provide an economical method for intercepting and diverting or collecting shallow ground water plumes (less than 7.6 m deep). For deeper trenches and trenches which require special excavation, costs can increase by a factor of ten making the system uneconomical. The French drains do require electricity for operation of pumps and yearly maintenance. There is a possibility of leakage through the drain system if an impermeable barrier is not used on the downgradient site. If the drain is to be used only for ground water diversion, some leakage may not be a problem. However, if the drain is to intercept a contaminated plume, a barrier is recommended to prevent leakage. The cost of this barrier is small compared to the cost of the drain.

Table XII. Costs for French Drain at Rocky Mountain Arsenal

	Unit Price	Total Price
Trench excavation and backfill 1067 ml x 0.91 m wide x 8.2 deep = 8000 m^3	30.19/m^3	241,520
0.40 m perforated pipe (installed)	$50.79/m	54,192
30.4 m of 0.51 m riser pipe	$84.65/m	2,573
Two 21 hp turbine pumps, 500 gpm	$3255 ea	6,450
Total cost w/o liner		$304,735
Downgrade liner 8000 m^3		13,993
Total cost with liner		$318,728

VIII. WELLPOINTS

A. Background

Wellpoints are a system of shallow wells that consist of riser pipes connected to a common header pipe and a centrifugal pump. A typical wellpoint system is shown in Figure 16. The wellpoint system uses suction to extract the water from an unconfined aquifer. This feature limits their depth of extraction to a maximum of approximately 10 m. Maximum drawdowns that can be achieved with wellpoints are approximately 4.5 m. The radius of influence of the wellpoint is determined by the hydraulic conductivity of the aquifer and is usually small.

Wellpoints may be used upgradient from a lagoon or landfill to lower the water table and prevent interaction of the ground water with the waste. A system which uses this principle is shown in Figure 17. If the cone of depression does not extend into the waste and is not contaminated, the ground water can be reinjected via a trench downgradient from the waste. Wellpoints may also be used to remove contaminated ground water from the aquifer for treatment. This contaminated water must be treated before surface discharge or ground water recharge.

B. Construction Considerations

The use of a wellpoint system to either lower the water table or collect a contaminated plume requires a thorough hydrological study of the area. This study should include sampling wells to outline the extent of the contaminated plume, its depth, the needed drawdown to prevent ground water interaction with the waste and a pump test to determine drawdown and radius of influence.

The typical procedure for construction of wellpoints is to jet them in place with a high pressure jet pump. In this procedure, water under high pressure is forced through a pipe and nozzle into the bottom of the hole. The subsurface soil is carried to the surface between the pipe and casing by the returning water stream.

The wellpoints themselves consist of short pieces of well screen attached to 5 - 7.5 cm diameter riser pipes. The length of the riser pipes is determined by the depth of the ground water to be pumped or the depth of the contaminated plume. The distance between the riser pipes is determined by the hydraulic conductivity of subsurface soil. Usually this distance is 1 - 2 m. Each riser pipe is connected to a suction header which in turn is connected to a centrifugal pump. The suction header should be buried below the frost line to prevent freezing. All connections must be airtight. The pump evacuates the air from the header and wellpoints and the hydraulic pressure of the ground water forces the water up the evacuated wellpoints. The water collected can be discharged onto a stone filled trench (See Figure 17) or collected and treated, if it is polluted.
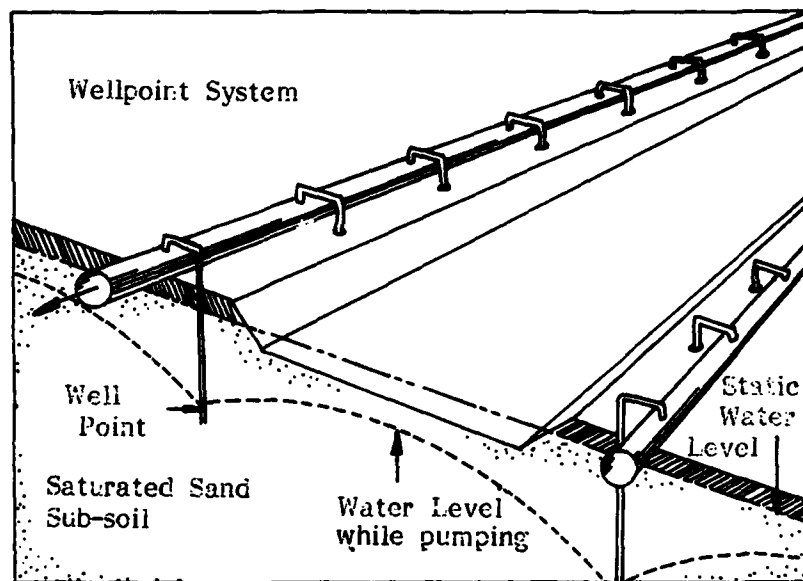
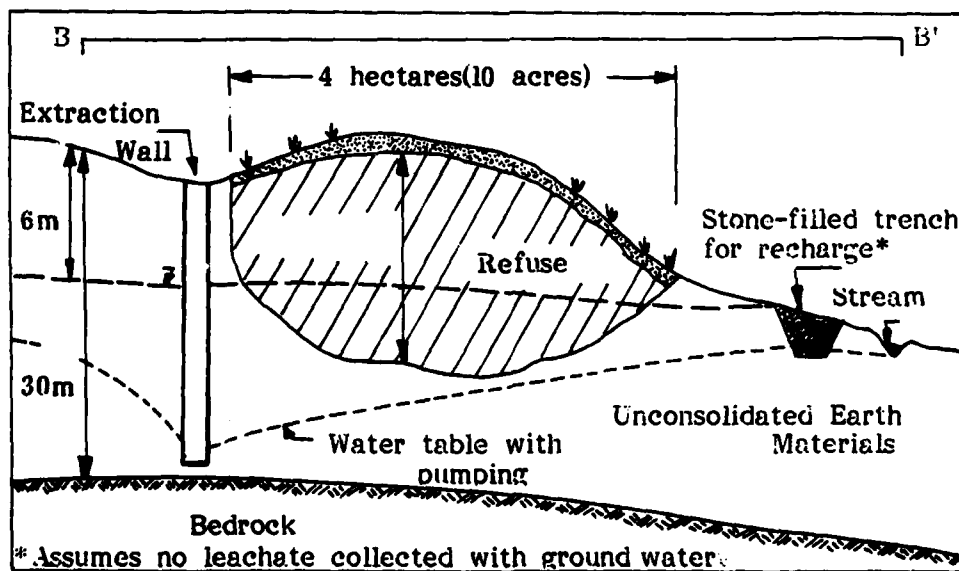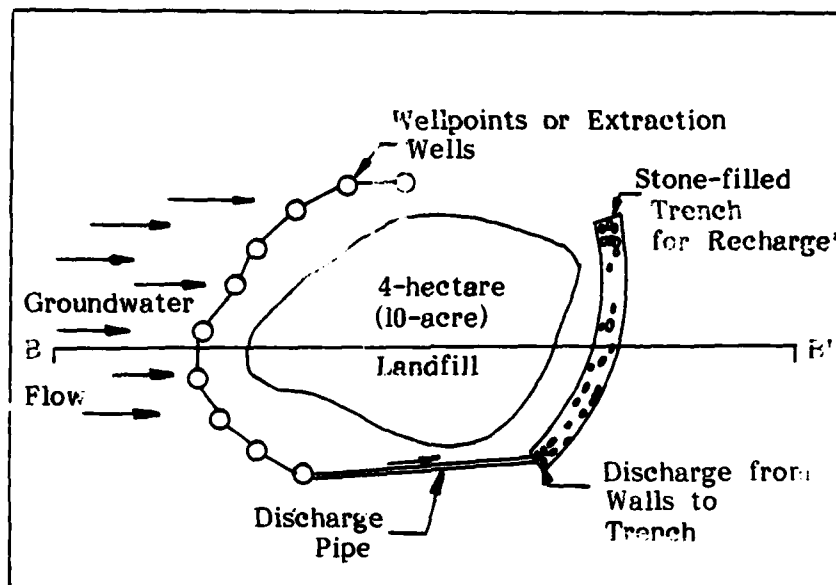Figure 16.   Wellpoint Dewatering System (Ulrich and Singer, 1973)

Figure 17. Plan View of Wellpoints or Extraction Wells Used to Lower Water Table Upgradient from a Landfill (Tollman et al., 1978)

C.   Performance

A wellpoint system was installed at the Defense Fuel Support Point in Charleston, South Carolina to collect JP-4 fuel which had leaked out of a storage tank and contaminated the ground water (Talts et al., 1977). A fifty point 2-line PVC well system was installed in an arc around the north/northwest section of the tank. These well points were set at approximately 17 ft below the ground surface. The points were located so that they intercepted the ground water every 1.5 - 2 m. The system operated for 5 weeks. The initial recovery rate was 2460 l/min. This rate decreased to approximately 114 l/min at the end of the 5 weeks. Approximately 25% of the spilled oil was recovered. Equipment rental and installation costs were $13,000. Operational costs were approximately the same amount. No indication was given as to whether the wellpoints allowed any of the fuel to leak past.

D.   Costs

The applicability of the wellpoint system at Rocky Mountain Arsenal may be limited by the depth of the contaminated ground water plume. Detailed geo-hydrological information would have to be evaluated to determine applicability of this system to the Rocky Mountain Arsenal. However, for cost comparison with other methods, it is assumed the wellpoint system would be applicable. Two wellpoint systems were evaluated in this analysis. The first system has the points spaced at 2 m interval. In the second system, the points are located on 1.5 m centers. Two centrifugal pumps capable of pumping 1500 - 1900 l/min will be sufficient to pump the peak ground water flow (37,850 l/hr for 427 m or 94,625 l/hr) across the 1067 m boundary (Thomas et al., 1977). Based on an estimated hydraulic head of 25.3 m (7 wellpoint and 18.3 m fractional loss in the header pipe), these pumps would have to be 21 hp. The wellpoints would preferably be arranged in a two-line system with a pump attached to each system header suction pipes.

The cost data (based on escalated figures from Tolman et al., 1978) are presented in Table XIII. Capital costs range from $45,494 to $73,202 for the 2 m center-to-center system and $55,504 to $88,213 for the 1.5 m center-to-center system.

The wellpont system requires continued maintenance and electrical costs. For a ten year operational period, the first year's costs are estimated as follows:

Labor/yr	$12,100
Materials/yr	1,400
Power/yr (two 21 hp pumps each operating 85% of the time) @ 0.06 KWH	$14,000
TOTAL/yr	$27,400

With an escalation rate of 12%/yr, the total operational costs for 10 years would be $479,500. The total investment for this type of barrier would be:

-    $392,994 to $420,702 for 2 m centers

-    $403,004 to $435,713 for 1.5 m centers

Table XIII.   Cost Data for Wellpoints for Rocky Mountain Arsenal

Wellpoint $12.90 - $19.35/unit
    Placement every 2 m = 535 points $ 6,902 $10,352
    Placement every 1.5 m = 711 units   9,172   13,758

Suction header $8.51 - $16.90/m   10,212   20,280

Suction pump (2) 400-500 gpm @ $2580-
    3870/1200 m   5,160   7,740

TOTAL

    For placement every 2 m $22,574 $38,374

    For placement every 1.5 m   24,544   41,778

E.   Advantages and Disadvantages of Wellpoints

Wellpoint construction is common and can be done at a very small cost per point. The construction is simple and can be accomplished by any qualified local contractor. This type of system can provide a good barrier to passage of a contaminated ground water plume at low capital costs.

Wellpoints are limited in their usefulness to shallow unconfined aquifers located at depts of up to 9.2 m. In addition to the shallow depth limitations, wellpoints have several other disadvantages. These disadvantages include high power costs and continuous maintenance to insure that the suction is maintained, thus long term commitments of power and manpower are necessary. The drawdown of the aquifer may also be a problem in some areas. Recharge into the aquifer may be necessary which constitutes additional capital and operating expenses. If the water is contaminated, it will also have to be treated before recharge. Treatment system installation and operation can vary from $50,000 to over $1,000,000 depending on the type and level of treatment necessary.

IX. WELL SYSTEMS AS HYDROLOGIC BARRIERS

A.   Background

Well systems can be used to dewater an aquifer located at depths to several hundred meters. Well systems are usually used in ground water control when the aquifer depth exceeds that for which wellpoints are usable (approximately 9 m) (Tolman et al., 1978; Contreau, 1979; Geraghty and Miller, 1978). This type of system can be used to control ground water upgradient from a lagoon or landfill or to remove a contaminated plume downgradient. As with well points, the clean water pumped may be used, discharged to surface water, or recharged into the aquifer via a downgradient trench or well. If the water is contaminated, it must be treated before recharge or discharge.

B.   Construction Considerations

As with wellpoints and other type of ground water barriers, the deployment of wells for ground water control is highly dependent on the site. A thorough geohydrological survey of the site is therefore the first step in determining the applicability of a well system to the problem and in the engineering design of the system. The location and spacing of the wells is determined by the permeability of the subsurface soils. For a well system to provide a good barrier, the cones of depression of the individual wells must overlap. The wells should be properly screened so the desired plume is pumped. This factor is particularly important if a contaminated plume is to be removed and prevented from reaching downgradient areas. Improper screening will result in leakage of the barrier or pumping of large volumes of clean water.

Water well drilling is a common construction technique. A variety of equipment is available for drilling wells including percussion, core, auger, and rotary rigs. The drilling technique used is dependent on the type of soil conditions encountered. Rigs with combinations of drilling capabilities are also available. A consideration in selecting the drilling techniques for a well is the use of drilling muds. The primary purpose of drilling muds is to fill the voids in the sides of the holes to prevent collapse of the sides during drilling. The presence of these muds essentially halts the in-flow of ground water and may be detrimental to pumping of the well. Even some of the less stable muds such as "Revert" are difficult to remove.

The wells must be of sufficient diameter to house the submersible pump (at least 10 cm) and to accomodate the expected output flows (Tolman et al., 1978; Department of Economic and Social Affairs, 1975). The casings and screens of the wells must be selected so that they can resist the lateral thrust of the pumped water, corrosion from the ground water or contaminants and encrustations (Department of Economic and Social Affairs, 1975).

Table XIV. Well Systems Used in Pollution Control

Pottstown, PA	Landfill Lagoons	SO₂ scrubber wastes, organics, PVC sludge	22 wells, 3 wells 60-120 m deep with total draw of 570 l/min - used for potable water, 5 wells near lagoons and landfill with draw of 370-750 l/min each; used for process 14 monitoring wells	100% effective in preventing pollution from migrating off-site	$250,000	SCS Engineers 1980
Myerstown, PA	Lagoon	Arsenic wastes	Installed 7 purge wells initially to remove As from ground water. Installed additional 7 wells to form cone of depression. Wells ranged in depth from 21 to 48 m and draw rate from 36-303 l/m	Decrease As conc. from 10,000 ppm to 100 ppm	-	SCS Engineers 1980
Woodbury, MN	Surface impoundment	Spent solvents, acid sludge	4 barrier wells installed; wells 1 and 3 draw from uncontamin aquifer at draw rates of 380 and 1890 l/min, respectively. Wells 2 and 4 draw from contaminated aquifer at draw rates of 2650 and 4540 l/min, respectively. Sixty percent of withdrawn water is used as cooling water by plant, the remainder is mixed and discharged into the Mississippi River	Appears to be effective in preventing off-site migration	Capital costs unknown $95,000 annual operating costs	SCS Engineers 1980
New Castle County, DL	Landfill	Metals, COD, BOD	Series of counter-pumping wells to prevent contamination of water company wells. Wells installed in 1973 and were pumping 3.54M gpd of contaminated water in 1974. The recovered water is settled, oxidized and allowed to flow into the Delaware Estuary and Columbian Formation	Successful	-	Clark, 1980
Franklin County, PA	Landfill	General refuse	Ground water run-off of 0.3 gpm/acre for this 15 acre site. This ground water is being collected by 4 pumping wells ranging in depth from 4.3 to 18.3m. Wells are automatically activated by float controls and pump contaminated water into a perimeter drain which empties into a leachate system.	Successful	$4,580 including wells and treatment system but not drains. Yearly costs for well operation are $173.	Hensley and Koster, 1980

C.   Performance

Dewatering a contaminated aquifer by pumping has been widely used as a ground water barrier for control of the spread of pollutants. A partial list of the projects which have been put into operation is given in Table XIV. Most of these projects have been successful in removing the contaminated water from the aquifer. However, little information is available on "leakage" of these barriers.

In most cases of pump-back for control of contaminated aquifers, recharge of the aquifer is not of primary concern. Therefore, the pumped water is treated to remove the contaminants and discharged to surface waters or a trench. The contaminated aquifer at Rocky Mountain Arsenal is the source of water for homes downgradient from the arsenal. Since the source of the pollutants is more or less constant, any cutoff of ground water would have to be long-term and would have deleterious effects on the area. To combat this problem, a pumping back recharge system was designed by the Waterways Experimental Station (WES). This barrier well system was reviewed by Thomas *et al.* (1977). In their opinion, the system proposed by WES would "leak"; in other words, contaminated water would pass by the pump-back wells. Thomas *et al.* (1977) proposed an alternative pump-back/recharge well design. Using computer analysis, they concluded that no pump-back/recharge system would work in steady-state operations at Rocky Mountain Arsenal, *i.e.* "Simultaneously capture all downgradient flow and prevent all flow between the dewatering and recharge lines." The aquifer will either be drawn (stop all downgradient flow, but allow upgradient flow from recharge wells) or will "leak" (allow some downgradient flow to pass the dewatering wells). Based on these results, Thomas *et al.* (1977) concluded that the pump-back/recharge system could not be used to meet ground water standards and still maintain the aquifer water table over the long term. However, from the limited information available, it appears that a dewatering system upgradient from the Basin F lagoon to control the leaching into ground water was not evaluated.

Other types of hydrological barriers have been extensively studied and used to prevent intrusion of saline waters into fresh water aquifers (Coe, 1972; Department of Water Resources, 1975; Sheahan, 1976; Williams, 1976, etc.). For this purpose, an injection well injects reclaimed or piped in water into the aquifer and an extraction well removes the water from the aquifer creating the situation shown in Figure 18. These types of hydrologic barrier are in place in San Francisco and in the Dashte-Naz farm area in Iran. The San Francisco installation injects reclaimed water into the aquifer to form a barrier against the saline water intrusion. The pumped back reclaimed water is sold to industry (Sheahan, 1976). In the Dashte-Naz project, water is piped in from wells located several miles inland during the winter months. This water is stored in the aquifer and pumped out for farm irrigation during the summer (Williams, 1976). Both projects appear to be meeting their objectives.

The use of air to control ground water movement has been suggested (Roberts, 1977). This type of hydrological control of saline water intrusion or ground water plume control could be less expensive than water pumping. However, the technique has not been tried in the field for this purpose.
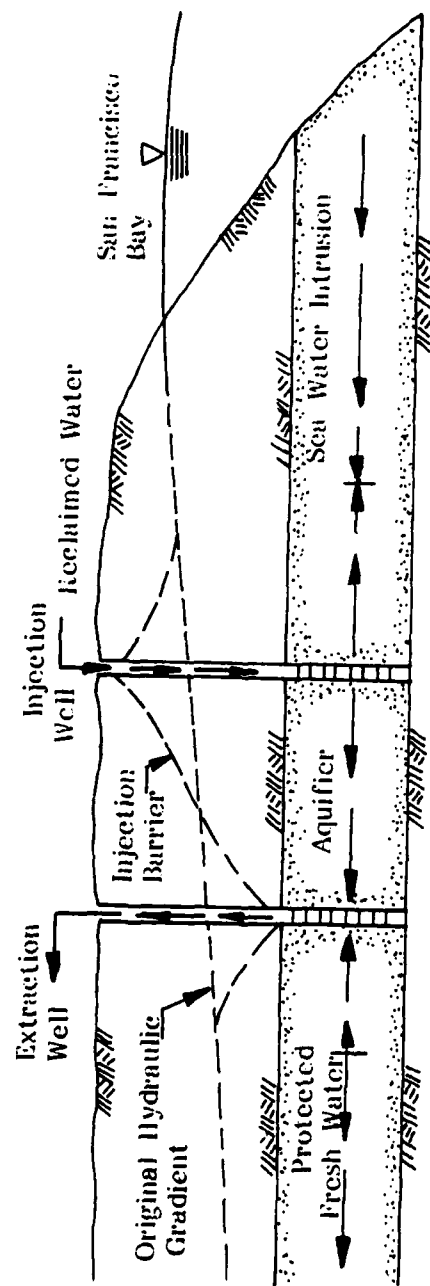
Figure 18. Diagrammatic Illustration of Operation of Injection/Extraction Doublet (Sheahan, 1976)

D.   Costs

The costs for a well pumping/recharge system (hydraulic gradient concept) for Rocky Mountain Arsenal were computed by Thomas et al (1977). These costs, updated to 1980 dollars using the CE cost index are presented in Table XV. The costs are based on 84 m centers, however, the pattern and details were not given. Annual operating costs for this system were estimated to be approximately the same as the wellpoint system. Thus, total investment for 10 years of operation would be $817,365. Without the recharge system, total investment would be $717,110.

E.   Advantages and Disadvantages of Well Systems

The well pump back system has advantages and disadvantages similar to the wellpoints. The advantages include:

-    simple construction

-    low capital costs

-    removal of any contaminated plume from the aquifer

Disadvantages include:

-    high maintenance and operating costs

-    long term committment of manpower and materials

-    drawdown on aquifer

-    additional costs and problem if recharged into the aquifer is necessary

-    additional costs for treatment of contaminants in water

Table XV. Costs for Hydraulic Gradient System for
Rocky Mountain Arsenal

Dewatering wells and equipment	
17 x $9804	$166,670
Recharge	58,050
Collection Pipe	63,340
Electrical distribution	15,100
Recharge trans.	30,190
Distribution pipe	4,515
TOTAL	$337,865
Without recharge	$237,510

X. AN ASSESSMENT OF PHYSICAL AND HYDROLOGICAL GROUND WATER CUTOFF BARRIERS

A comparison of the available types of ground water cutoff barriers is given in Table XVI. Included in this table are construction costs for the barriers, advantages and disadvantages of the barriers, applicable scenarios for ground water cutoff and advantages and disadvantages of the barriers as applied to the scenarios. The costs presented are for the construction of the barrier only. They do not include preconstruction site surveys, contaminated ground water treatment systems, ground water recharge systems, or yearly maintenance and operating costs. If any of these ancillary items is necessary, its cost must be added to that shown in the table.

Inspection of the table shows that the hydrological barriers, French drains, wellpoints and deep wells, are the least expensive cutoff barriers to install. However, they have high yearly maintenance and operating costs. There is also the possibility of leakage past these barriers. The Imper-wall and slurry-trench are the least expensive physical barriers. The barriers themselves require little or no maintenance. However, if pumping, treatment and recharge is necessary for the site, the capital costs can increase significantly. This situation also introduces high yearly operating and maintenance costs. Sheet pilings have never been used for pollution control. Their costs rank between slurry-trenches and grout curtains. Grout curtains are the most expensive ground water cutoff walls. They are also the most difficult to install and their technical performance is very site dependent.

Based on the state-of-the-art in ground water cutoff barriers, the hydrological barriers and the slurry-trench and Imper-wall are the most cost effective barriers. However, selection of one of these barriers over the other is not a simple matter. A detailed knowledge of the objectives of the barrier and the subsurface features of the site (Phase I) must be known and evaluated before a type of barrier and its materials of construction can be selected (Phase II). Thus, each site is an individual entity which must be evaluated for itself. The barrier then must be engineered, a preliminary cost analysis performed and a construction contractor selected (Phase III). The barrier construction is then undertaken (Phase IV). Upon completion, the barrier is monitored to determine its performance characteristics (Phase V). The cost analysis is done by an engineering firm and the actual construction by another contractor. These firms may or may not talk to each other. Thus, the costs and technical problems may be very different from what the customer was led to believe. A case in point, is the remedial action at the Love Canal. The engineering firm estimated $1.4 million for the Phase I remedial action. Costs incurred to October, 1979 were $6.5 million and Phase I was not completed (Glaubinger et al., 1979). A few European firms with branches in the U.S. provide the customer with total service. It is recommended that persons seeking to use ground water barriers for pollution control employ a firm that is well known in the area and can do the whole job.

There are three items that must be recognized before a ground water barrier is considered.

1. No barrier is completely impermeable

Table XVI. Comparison of Ground Water Cutoff Barriers

Advantages of Method in General	Disadvantages of Method in General	Method of Application to Landfill or Lagoon Leachate Control
I. SB Slurry-trench		
a. Construction methods are well established and require no exotic equipment	a. Presence of high ionic strength leachates requires use of chemically resistant bentonites	1. Diversion barrier to divert ground water around lagoon or landfill
b. Little or no maintenance is required after wall is in place	b. Rocky terrain makes trenching difficult and can result in over excavation	
c. Can be placed in mobile soils	c. Backhoes can leave furrows in bottom of wall	
d. If proper compatability studies are run, the bentonite will not deteriorate with age	d. Walls have no load bearing strength	2. Contain downgradient contaminated ground water plume
e. Uses available soil as back-fill	e. Sufficient area must be available for backfill operations	
f. Barrier has no vertical seams	f. If wall is severely damaged, it is not easy to repair	
	g. If impervious soil layer is very deep (greater than 12.2 m), the trenching operation is costly	
	h. Wall may not be homogeneous if back fill operation is not performed correctly	
		3. Completely surround landfill or lagoon
II. CB Slurry-trench		
a. Construction methods are well established and require no exotic equipment	a. Cannot be used in presence of sulfate. acids, salts	1. Diversion barrier to direct ground water around lagoon or landfill
b. Little or no maintenance is required after wall is in place	b. Rocky terrain makes trenching difficult and can result in over excavation	
c. Can be placed in mobile soils	c. Backhoes can leave furrows in bottom of wall	2. Contain downgradient contaminated ground water plume
d. Barrier has no vertical seams	d. If impervious layer is very deep (greater than 12.2 m), the trenching operation is costly	
e. Walls have greater load bearing capacity than SB walls	e. May require use of a specific contractor due to patent restrictions	3. Completely surround lagoon or landfill
f. Does not require presence of suitable backfill soil or area for backfill operations		
g. Wall is more homogeneous than SB and thus can be thinner		
h. Easy to repair, keys into itself easily		

Table XVI. (continued)

Cost for .067 m x 5.2 m Barrier	Additional Costs of Specific Application	Advantages of Specific Application	Disadvantages of Specific Application
		I. SB Slurry-trench	
$662,000 (chemically resistant bentonite) $378,000 (normal bentonite)	1. none	1a. Can significantly reduce water seepage into lagoon or landfill b. Will not drawdown the aquifer c. Unless upgradient ground water is poor quality, does not require special bentonites	1a. Will not prevent leachate and ground water contamination due to surface infiltration
	2a. Costs for dewatering wells b. Yearly operating and maintenance costs for dewatering wells c. Treatment system for contaminant removal d. Yearly operating and maintenance costs for treatment system e. Recharge wells or trenches, if necessary to maintain water table f. Yearly operating and maintenance for recharge	2a. Can lower downgradient ground water contamination b. Can maintain water table level if recharge wells are used	2a. High capital and operating costs b. Not a solution to the problem c. Cannot contain 100% of the contaminants d. Requires use of chemically resistant bentonite
	3. Same as 2a, b,c,d	3a. Can contain leachates b. Will not affect water table level downgradient	3a. High capital and operating costs b. Requires use of chemically resistant bentonite
		II. CB Slurry-trench	
$662,000	1. None	1a. Can significantly reduce water seepage into lagoon or landfill b. Will not drawdown the aquifer	1a. Will not prevent leachate and ground water contamination due to surface infiltration b. Cannot be used if upgradient water contains high concentrations of sulfates, is acidic or saline
	2a. Same as I. 2a-f	2a. Same as I. 2a,b	2a. Same as I. 2a-c d. Cannot be used in presence of sulfates, acids or salts
	3a. Same as I. 3a-d	3a. Same as I. 3a.b	3a. High capital and operating costs b. Cannot be used in presence of sulfates, acids or salts

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Table XVI. (continued)

Cost for .067 m x 8.2 m Barrier	Additional Costs of Specific Application	Advantages of Specific Application	Disadvantages of Specific Application
		III. Grout Curtain	
	I. None	1a. Can significantly reduce water seepage into lagoon or landfill	1a. Will not prevent leachate and ground water contamination due surface infiltration
		b. Will not drawdown the aquifer	b. Not applicable to soils with permeability $< 10^{-5}$ cm/sec
			c. Can be washed out of place by ground water flow before set
	2a. Costs for dewatering wells	2a. Can lower downgradient ground water contamination	2n. Very high capital and high operating costs
	b. Yearly operating and maintenance costs for dewatering wells	J. Can maintain water table of of recharge wells are used	b. Not a solution to problem
Cement (2 rows)		c. Treatment systems for contaminant removal	c. Not applicable to soils with permeability less than 10^{-5} cm/sec
$378,000-1,862,600		d. Yearly operating and maintenance cost for treatment system	d. Can be washed out of place by ground water flow before set
		e. Recharge wells or trenching if necessary to maintain water table	e. Not applicable to soils with permeability less than 10^{-5} cm/sec
Silicate (15%) (2 rows)		f. Yearly operating and maintenance for recharge	
$2,953,500	3. Same as 2a, b, c, d	3a. Can contain leachates	3a. Very high capital and high operating costs
		b. Will not affect water table level downgradient	b. Requires use of chemically resistant grout material
		c. Treatment system for contaminant removal	
		d. Yearly operating and maintenance costs for treatment system	
		e. Recharge wells or trenches, if necessary to maintain water table	
		f. Yearly operating and maintenance for recharge	

Acrylamide

$2,953,000

Isocyanate

$2,904,900 -$7,512,400 depending on whether cement is used with it or not

Table XVI. (continued)

Advantages of Method in General	Disadvantages of Method in General	Method of Application to Landfill or Lagoon Leachate Control
IV. Imper-Wall Curtains		
a. Construction costs less than grouting	a. Requires elaborate equipment which is subject to breakdown	1. Diversion barrier to divert ground water around lagoon
b. Does not require as elaborate preconstruction studies as grout curtains	b. Construction technique is not as well developed as slurry-trench or grouting	
c. Uses less materials than a grout curtain or slurry-trench	c. Limited to depth of 15 m	
d. More expensive materials can be used if very low permeability is needed		2. Contain downgradient contaminated ground water plume
e. Improved permeability characteristics of surrounding soil as a result of compaction		
		3. Completely surrounds landfill or lagoon
V. Sheet-piling Cutoff Wall		
a. Construction is straight forward	a. Pilings are not initially water-tight	1. Diversion barrier to divert ground water around lagoon or landfill
b. Requires little or no maintenance after installation	b. Construction in rocky terrain is difficult	
c. Protective coatings can be applied to resist corrosion	c. Threat of corrosion by exotic chemicals	2. Contain downgradient contaminated ground water plume
d. Contractors are available throughout the U.S., thus, mobilization costs are low	d. Never been used in pollution control	
	e. More expensive than proven methods	3. Completely surround landfill or lagoon
VI. French drains		
a. Construction method simple	a. Continued maintenance is necessary	1. Upgradient removal/downgradient recharge
b. Useful for shallow aquifer	b. Operating costs are high	
c. Technology well established	c. Requires long-term manpower and materials committment	
	d. Costs increase if aquifer is deep or if specialized trenching is required	
		2. Downgradient leachate collection
VII. Wellpoints		
a. Common construction techniques	a. Require extensive site surveys	1. Upgradient removal/downgradient recharge
b. Technology available throughout the U.S.	b. Not applicable to depths > 9.2 m	
c. Low capital costs	c. High operating costs	2. Downgradient leachate collection
	d. Long term committments of manpower and materials	
	e. Additional costs if recharge is necessary	
	f. Requires large number of wellpoints	
	g. Air-tightness of suction header must be maintained	
	h. Aquifer drawdown if no recharge is used	
VIII. Deep wells		
a. Simple construction	Same as VII a-e, h	1. Upgradient removal/downgradient recharge
b. Low capital costs		2. Downgradient leachate collection
c. Technology available throughout U.S.		

Table XVI. (continued)

Cost for 1067 m x 8.2 m Barrier	Additional Costs of Specific Application	Advantages of Specific Application	Disadvantages of Specific Application
		IV. Imper-Wall Curtains	
Cement $301,500 - $419,600	1. None	1a. Can significantly reduce water seepage into lagoon or landfill	1a. Wall will not prevent leachate and ground water contamination to surface infiltration
		b. Will not drawdown the aquifer	b. Not applicable to clays
			c. Cement cannot be used in presence of saline, and/or high sulfate waters
Aspermix $419,600 - $431,600	2. Same as III 2a-f	2. Same as III 3a, b	2a. Not a solution to the problem
			b. Cannot contain 100% of the contaminant
			c. Cement and Aspermix cannot be used with high organic salts
	3. Same as III 2a, b, c, d	3. Same as III 3a, b	3. Same as 2a-c
		V. Sheet-piling Cutoff Wall	
$725,000 - $1,230,000	1. None	1a. Can reduce seepage	1a. Will not prevent leachate and ground water contamination due to surface infiltration
		b. No drawdown on aquifer	b. May require protective coating
	2. Same as I 2a-f	2. Same as I 2a, b	2a. Same as I 2a-c
			b. Requires protective coatings
	3. Same as I 2a-f	3. Same as I 3a, b	3. Same as I 3a
		VI. French drains	
unlined $304,735	1a. Downgradient recharge trench	1a. Prevents interaction of ground water with landfill	1a. Will not prevent leachate and ground water contamination due to surface infiltration
		b. No drawdown of aquifer if downgradient recharge is used	
lined $318 - $728		c. Liner may not be necessary	
	2a. Treatment system	2a. Lower downgradient contamination	2a. Operating costs are high
	b. Yearly maintenance and operating costs for treatment system	b. Can maintain water table level if recharge is used	b. Requires liner
	c. Recharge trench		c. Liner could fail or lift allowing escape of contaminated water
		VII. Wellpoints	
$45,494 - $88,213	1. Same as VI a	1. Same as VI 1a, b	1a. Same as VI 1a
			b. Applicable only to depth less than 9.2 m
	2. Same as VI 2a-c	2. Same as VI 2a, b	2a. Operating costs are high
			b. Pump failure could cause significant leakage
			c. Applicable only to depths less than 9.2 m
		VIII. Deep wells	
$237,510	1. Same as VI 1a	1. Same as VI 1a, b	1. Same as VI 1a
	2. Same as VI 2a-c	2. Same as VI 2a, b	2a. Operating costs are high
			b. Will not operate at steady-state-leak or aquifer drawdown

2.   No barrier will last forever

3.   A ground water barrier only treats the symptoms
     of a pollution problem, it does not solve the problem.

All barriers will "leak" to some degree, thus, a continuous, well-planned monitoring schedule will have to be maintained until the source of the contamination is removed. This monitoring task will also indicate flaws which may develop in the barrier. Even the maintenance free slurry-trench barriers will fail due to ground movements, burrowing animals and insects, infiltration by roots, etc. The most important point is that a ground water barrier is not a solution to a pollution problem. The tendency has been to construct the barrier, congratulate each other for a job well done, complain about the cost and walk away and forget the source of the problem. Eventually the barrier will fail, the laws will change, etc. and the decontamination of the source will again rear its ugly head. The questions which must be answered are then:

1.   Is the technology available to decontaminate the source?

2.   Would it be more cost effective to decontaminate the
     source now or construct a costly barrier and decontaminate
     it later?

Finally, it is recommended that a data base on applications of ground water cutoff barriers be established. This data base should include:

-   site geohydrological information

-   chemical contaminants

-   type of barrier

-   materials of barrier construction

-   method of barrier constructon

-   contractor

-   costs

-   permeability of the constructed barrier

-   any failure or problems with the barrier

-   monitoring

Private firms who have had ground water barriers constructed on their site should be encouraged to provide information on their barrier. This type of information is not currently available, hiding under the guise of "proprietary." The absence of specific ground water barrier information will result in needless future expenditures on barriers which do not perform their intended function.

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A
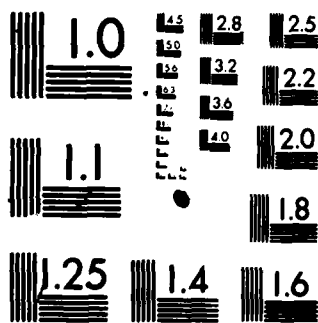
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